Economic Critical Resources for the Industrial Exploitation of Natural Gas Hydrate

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Abstract: Since the implementation of several pilot production tests were in natural gas hydrate (NGH) reservoirs in terrestrial and marine settings, the study of NGH has entered a new stage of technological development for industrial exploitation. Prior to the industrial exploitation of any given NGH reservoir, the economic feasibility should be examined. The first step of economic evaluation of a NGH reservoir is to know whether its resource amount meets the requirement for industrial exploitation. Unfortunately, few relevant studies have been conducted in this regard. In this study, the net present value (NPV) method is employed to estimate the economic critical resources required for the industrial exploitation of NGHs under different production scenarios. Sensitivity analysis is also performed in order to specify the effects of key factors, such as the number of production wells, gas price, technological improvement and tax incentive, on the economic critical resources. The results indicate that China requires the lowest economic critical resource for a NGH reservoir to be industrially exploited, ranging from 3.62 to 24.02 billion m^3 methane. Changes in gas price and tax incentives also play significant roles in affecting the threshold and timeline for the industrial exploitation of NGH.

Key words: natural gas hydrate, industrial exploitation, economic critical resource, net present value, recovery factor

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1 Introduction

The increasing conflict between economic growth and climate change requires a transformation in energy use. With global attention focused on climate change, carbon peaking and net zero carbon, a reduction in CO_2 emissions is underway due to government regulations and market forces. An energy mix completely reliant on renewable energy may be in our future, but its timing is very uncertain, as renewable energy presently contributes only a small fraction of energy supply (Max and Johnson, 2019). In the transition to a renewable energy future, natural gas is expected to be the cleanest hydrocarbon fuel (Chong et al., 2016; Max and Johnson, 2019), as burning natural gas for the same amount of energy results in the lowest carbon dioxide emission.

The growing demand drives research interest in broadening gas sources, including the commercialization of unconventional natural gas (Vedachalam et al., 2015). Potentially the largest natural gas resource remaining on Earth, marine natural gas hydrate (NGH) may provide a substantial natural gas supply far into the future (Max and Johnson, 2019). NGH is an ice crystal-like compound formed by gas molecules and water molecules under high pressure and low temperature conditions. Since the 1960s, researchers have gradually discovered more and more natural gas hydrates existing in the sediments of both seabed and permafrost (Sloan and Koh, 2007). Natural gas hydrate resource assessments indicate a large amount of methane in hydrates around the world, which is becoming one of the main driving forces behind attention on NGHs (Chen et al., 2021). Therefore, many countries that lack conventional resources within their jurisdiction but possess large hydrate reserves, such as Japan, exploit NGH to reduce their dependence on imports (Oyama and Masutani, 2017).

Renewable energy is characteristically intermittent, so at current levels of technology there will be a need for natural gas for a considerable time. Max and Johnson (2019) argued that the sooner alternative energy sources can be implemented, the easier will be the passage to the new energy paradigm in which renewable energy will be dominant. However, in the future (beyond 2060), when net zero caron emission is reached, no conclusion has yet been reached on whether NGH will be part of a solution or problem for China, in terms of CO_2/methane emissions.

So far, at least 30 estimates of global NGH have been published in a variety of studies (Table 1). In 1973, Trofimuk et al. evaluated the global NGH resources for the first time; the in-situ estimate was 3.02–3.09 × 10^{18} m^3

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Table 1 Estimated resources of natural gas hydrates in the world

No.	GIP[a] of NGH ($\times 10^{15}$ m^3)	TRR[b] considered	ERR[c] considered	Method	Reference
1	3053	Not	Not	Volumetric	(Trofimuk et al., 1973)
2	1135	Not	Not	Volumetric	(Trofimuk et al., 1975)
3	1573	Not	Not	Volumetric	(Cherskii and Tsarev, 1977)
4	1550	Not	Not	Volumetric	(Nesterov and Salmanov, 1977)
5	120	Not	Not	Volumetric	(Trofimuk et al., 1979)
6	3.1	Not	Not	Volumetric	(McIver, 1981)
7	15	Not	Not	Volumetric	(Trofimuk et al., 1983)
8	40	Not	Not	Volumetric	(Kvenvolden, 1988)
9	20	Not	Not	Volumetric	(MacDonald, 1990)
10	26.4	Not	Not	Volumetric	(Gornitz and Fung, 1994)
11	0.48	Not	Not	Volumetric	(Harvey and Huang, 1995)
12	6.8	Not	Not	Volumetric	(Holbrook et al., 1996)
13	15	Not	Not	Volumetric	(Dickens et al., 1997)
14	15	Not	Not	Volumetric	(Makogon, 1997)
15	21	Not	Not	Comprehensive analysis	(Kvenvolden, 1999)
16	4	Not	Not	Volumetric	(Dickens, 2001)
17	0.21	Not	Not	Volumetric	(Soloviev, 2002)
18	4	Not	Not	Volumetric	(Milkov et al., 2003)
19	2.5	Not	Not	Volumetric	(Milkov, 2004)
20	5.7	Not	Not	Particle organic carbon deposition rate	(Buffett and Archer, 2004)
21	115.4	Not	Not	Volumetric	(Klauda and Sandler, 2005)
22	0.397	Not	Not	Volumetric	(Ge et al., 2005)
23	3.4	Not	Not	Particle organic carbon deposition rate	(Archer et al., 2009)
24	0.5	Not	Not	Particle organic carbon deposition rate	(Burwicz et al., 2011)
25	0.45	Yes	Yes	Comprehensive analysis	(Boswell and Collett, 2011)
26	1.0	Not	Not	Particle organic carbon deposition rate	(Wallmann et al., 2012)
27	1.05	Not	Not	Particle organic carbon deposition rate	(Pinero et al., 2013)
28	5	Not	Not	Comprehensive analysis	(Cong et al., 2014)
29	3.5	Not	Not	Particle organic carbon deposition rate	(Kretschmer et al., 2015)
30	0.041	Yes	Not	Statistical model	(Pang et al., 2021)

Note: GIP[a] = gas in place; TRR[b] = technically recoverable resource; ERR[c] = economically recoverable resource.

natural gas equivalent (Trofimuk et al., 1973), which is the maximum estimate of methane resources. Soloviev gave a minimum estimate of 0.2×10^{15} m^3 methane, considering some limiting factors such as the availability of methane, limited porosity and the percentage of organic matter (Soloviev, 2002). The gap between the maximum value and the minimum value is about four orders of magnitude. This is mainly due to the lack of consensus among different researchers on the nature, occurrence and even a clear definition of NGH resources, as well as the methods and data used for evaluation (Pang et al., 2021). Most resource estimates have shown a downward trend over time, with the exception of Klauda and Sandler (2005), whose estimate includes very deep and dispersed hydrates that are usually not taken into account by other researchers. All these differences reflect the continuous progress of human understanding of NGH (Chong et al., 2016). Although the specific estimates of NGH resources are different, the fact that there is a mass of natural gas in gas hydrate has been generally accepted (Koh and Sloan, 2007; Collett et al., 2015). Among the 30 estimates of global NGH resources, 24 estimates (Table 1) exceed the total amount of conventional natural gas resources in place of 0.67×10^{15} m^3 (Zou et al., 2015). As long as a part of these resources can be exploited commercially, the demand for natural gas consumption can be met for a long time to come (Demirbas et al., 2016). For example, according to the United States (U.S.) Geological Survey, about 2×10^5 trillion ft^3 of hydrates are available in the U.S. alone. The annual consumption of natural gas in the U.S. is about 22 trillion ft^3, which means that in the next 100 years, NGH can meet the needs of the U.S. at a recovery rate of 1% (Demirbas et al., 2016).

However, it is a significantly different proposition when global totals of gas hydrate are compared with their technically recoverable and economically recoverable counterparts (Boswell and Collett, 2011). In the past 40 years, most estimates have focused on the total amount of methane found in the form of hydrates, without considering the technical and economic recoverability of the resource. Boswell and Collett (2011) introduced the concepts of technically recoverable resource (TRR) and economically recoverable resource (ERR) of NGH resource assessment. They postulated that an initial order of magnitude estimate of TRR from gas-hydrate-bearing sand reservoirs is about 3×10^{14} m^3 (Boswell and Collett, 2011). Even now, it is impossible to accurately estimate the TRR of NGHs, because the technology for gas hydrate exploitation has not yet been determined and the resulting estimates are, at the very least, not rigorous. Furthermore, Boswell and Collett (2011) estimated the ERR of gas hydrate to be zero, although, at the time, the total production cost of hydrates (e.g., exploration, drilling, completion, stimulation and production) and the possible production over time were unknown. Many hydrate reservoirs were located in areas with limited natural gas markets or limited infrastructure to transport natural gas to remote markets. There is no evidence that NGHs are economically recoverable at prevailing natural gas prices (Boswell and Collett, 2011), although it should be noted again that their conclusions were obtained on the basis of the gas price around 2011. However, the gas price fluctuates as affected by the factors of economics, politics and nature. For instance, the gas price increased from about €20 to about €100 per megawatt hour in April-October 2021 in Europe, influenced by the factors of both weather and economic rebound as countries lifted Covid-19 restrictions (Euronews, 2021).

Prior to the commercialization of NGH, an economic evaluation must be carried out to determine whether it is profitable. The economic feasibility of an NGH exploitation project is affected by many factors. Choosing an exploitation target with a suitable scale of resources is the first step in studying the economics of a project. As mentioned earlier, there are few studies focused on economically recoverable resources of gas hydrate, due to a lack of available data. However, with the success of several trial productions of natural gas from onshore and offshore hydrate deposits, relevant knowledge and experience has been accumulated on how to more efficiently produce methane from gas hydrates. In addition, field testing has shown that gas can be produced from NGH using conventional offshore gas production facilities (Yamamoto et al., 2014; Collett et al., 2015; Li et al., 2018). Therefore, the data for conventional natural gas economic evaluation (e.g., capital expenditure) can be used as a reference for gas hydrate exploitation. The MH21-S R&D consortium estimated the economics of three hypothetical hydrate accumulations, located in the Nankai Trough, Japan, that differ in size of original resource, production period, number of production wells and productivity. The results show that the original methane in place in a concentrated zone and the average production rate per well need to be more than 60 billion m^3 and 300,000 m^3/day, respectively, in order to satisfy the requirement of an internal rate of return (IRR) of 10%, based on a liquefied natural gas (LNG) price of \$10/MMBtu (MH21, 2019). Although this result reveals that the exploitation of large-scale gas hydrate accumulations is more likely to achieve economic benefits, it does not clearly indicate the critical value of economically recoverable resources required for the successful industrial exploitation of NGHs. When gas hydrate research enters the stage of industrial exploitation, large-scale hydrate accumulations should be the first target objective. However, some hydrate reservoirs, having potential economic benefits, can also be considered. Therefore, exploring economic critical resources has a direct relevance for the overall industrial exploitation of gas hydrates. In terms of the timeline for the commercialization of hydrates, different organizations hold different views and plans (Ruppel, 2011). Estimating the economic critical resources will provide a much better understanding of the gap between current hydrate research and the final realization of commercialization.

The purpose of this research is to estimate the critical resources required for the commercialization of NGH under different production life models from an economic perspective, as well as exploring the key factors that affect economic critical resources. By referring to the cost data of conventional offshore natural gas extraction, the discounted cash flow (DCF) method is adopted to estimate the break-even production rate of a hypothetical exploitation project. Based on this, the economic critical resource for gas hydrate industrial exploitation with different production lifespans is estimated. Due to the different market conditions (e.g., natural gas prices) and economic policies (e.g., tax regulations) around the world, three countries that are leaders in the field of NGH research (Japan, China and the U.S.A.) were selected as the representatives for comparison. To reduce the resulting uncertainty from the limited data, sensitivity analysis was carried out on the main parameters that affect economic critical resources, such as the number of production wells, natural gas prices and tax reduction rates.

2 Methodology

2.1 Application of NPV method to the estimation of economic critical resources for NGH exploitation

In this research, the sales revenue and development costs of natural gas were estimated for hypothetical gas hydrate reservoirs in the Nankai Trough in Japan, the Shenhu area of the South China Sea and the Gulf of Mexico in the U.S.A.. The differences in natural gas prices and tax policies of these three countries were taken into account. The net present value (NPV) method is employed to estimate the break-even production rate required for the commercialization of NGH. NPV is defined as the algebraic sum of all future net cash flows when discounted to time zero (the first year of field development) (Masuda et al., 2010):

$$NPV = \sum_{t=1}^{n} (CI - CO)_t (1 + i_c)^{-t} \tag{1}$$

where NPV is the net present value; CI and CO represent the cash inflow and cash outflow, respectively; n is the production cycle of the field; t represents the t-th year in the life cycle of the field; $(CI - CO)_t$ refers to the net cash flow of year t; and i_c is the discount rate, which refers to the interest rate used in discounted cash flow (DCF) analysis, to determine the present value of future cash flows.

The future net cash flows are computed by subtracting the capital expenditure (CAPEX) and taxes (Tax) from the income from gas sale (Q_gP_g). Specifically, the CAPEX includes offshore production platform costs ($C_{platform}$), well drilling and completion costs (C_{well}), subsea system costs (C_{subsea}), pipeline construction costs ($C_{pipeline}$), operation costs ($C_{operation}$) and field abandonment cost ($C_{abandonment}$). Sales revenue is the product of gas production (Q_g) and gas price (P_g). Considering the discount rate or required return (i), the discounted cash flow of the t-th year [$(CI - CO)_t$] can be estimated by:

$$(CI - CO)_t = Q_g P_g - (C_{platform} + C_{well} + C_{subsea} + C_{pipeline} + C_{operation} + C_{abandonment} + Tax) \tag{2}$$

Then the NPV becomes

$$NPV = \sum_{t=1}^{n} \frac{Q_g P_g - (C_{platform} + C_{well} + C_{subsea} + C_{pipeline} + C_{operation} + C_{abandonment} + Tax)}{(1 + i_c)^t} \tag{3}$$

The break-even production rate (*BEP*) is the gas production rate of a well (m^3/day/well) when the *NPV* is equal to 0, which gives

$BEP = Q_g$ when

$$NPV = \sum_{t=1}^{n}(CI - CO)_t (1+i_c)^{-t} = \frac{Q_g P_g - (C_{platform} + C_{well} + C_{subsea} + C_{pipeline} + C_{operation} + C_{abandonment} + Tax)}{(1+i_c)^t} \quad (4)$$

This is the minimum production that can guarantee the financial profitability of a potential NGH exploitation project.

Multiplying the BEP by the number of wells and the effective production time results in the minimum total production required to ensure profitability over different project lifespans. In other words, to ensure the economic viability of a potential NGH exploitation project, the ERR of the target reservoir must be not less than the minimum total production under the same production circumstance. For simplicity, the minimum total production is treated as ERR or economic critical resource in this research.

According to the definition of EIA (EIA, 2014), ERR is a portion of TRR. TRR is a subset of gas in place (GIP) that is converted to TRR by multiplying itself by the recovery factor (RF) (Boswell and Collett, 2011). However, the quantitative relationship between ERR and GIP is difficult to determine. This is because ERR fluctuates over time in response to the changes in economic and regulatory conditions. Factors beyond simple economic criteria (e.g., national energy security) may impact policy and regulation, further impacting ERR (Boswell and Collett, 2011). This research assumes that ERR is a certain proportion of GIP. ERR is divided by the assumed proportion (also called the recovery factor) to obtain a rough estimate of GIP. The relationship between the three concepts GIP, TRR and ERR is depicted in Fig. 1.

As shown in Fig. 2, the same calculation process is applied to the three cases (Japan, China and the U.S.A.), so that any diversity within the results are only caused by the data differences resulting from the supply and demand of the natural gas sales market, the development level of the oil and gas industry, as well as the taxation policies in the three countries.

2.2 Assumptions of the model

It should be noted that the longest duration of the production test is 60 days, which is much less than the life cycle for industrial exploitation (which would be around 10 years, or even longer). Long-term gas production behavior is still uncertain, leaving various levels of uncertainties, such as the capacity of production facilities for future industrial exploitation. Therefore, for economic evaluation, it is necessary to make a range of assumptions to supplement such uncertainties. The main assumptions for economic evaluation are as follows:

(1) The research is based on hypothetical NGH reservoirs in the Nankai Trough in Japan, the Shenhu area of the South China Sea and the Gulf of Mexico in the U.S.A.. The specific geological conditions and production potential of these reservoirs are not considered, because

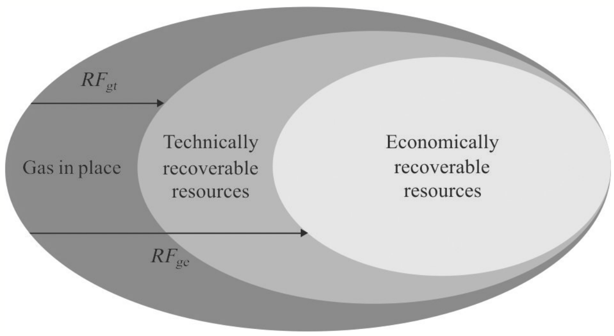

Fig. 1. The relationship between gas in place (GIP), technically recoverable resources (TRR) and economically recoverable resources (ERR).

Resource categories are not drawn to scale relative to the actual size of each resource category. RF_{at} and RF_{ae} refer to the recovery factor multiplied by when GIP is converted to TRR and ERR, respectively.

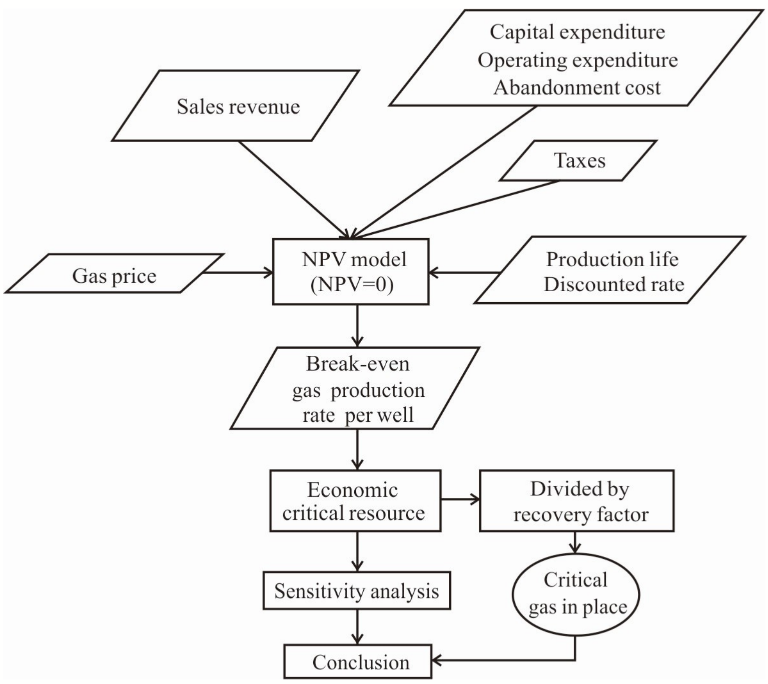

Fig. 2. Schematic of the study method.

they are beyond the scope of this research.

(2) The amount of gas in place is assumed to be a ratio of economically recoverable resources to a recovery factor.

(3) The gas production rate is constant during the production period.

(4) The effective production days of each year are 347 days (95% of 365 days).

(5) All wells are drilled during the construction period, which is set to 1 year.

(6) The first production year is set as 2030.

(7) The gas produced is sold on the domestic market, after being transported ashore.

(8) Like other unconventional natural gas resources, the exploitation of NGHs will first experience an increase in production brought about by technological progress and then a decline in production caused by physical resource depletion over time (Dale et al., 2012). Operating costs are jointly affected by technological progress and resource depletion. The operating costs are assumed to decrease and increase at two constant rates in different stages of the production life (Table 2).

(9) The early stage of commercialization of NGHs may need policy support, such as tax relief. Within the first 3/5 of production life, the government provides subsidies in the form of tax reductions with different reduction rates (Table 3).

2.3 Data estimation

Capital expenditure (CAPEX) mainly includes the costs of production facilities, production wells and subsea pipelines. Field testing has shown that gas can be produced from gas hydrate using conventional offshore gas production facilities (Yamamoto et al., 2014; Collett et al., 2015; Li et al., 2018). Although it has been suggested that these heavy-duty facilities are much more costly and less efficient than those dedicated to NGH exploitation (Max and Johnson, 2019), specialized facilities for gas hydrate exploitation have not thus far been developed. As a result, conventional offshore gas production facilities have been adopted as the model of utility in this research. The water depth of NGH reservoirs is usually about 1000 m, with a burial depth of 300–500 m below the seabed (Max and Johnson, 2019). The production platform with a suitable operating depth is determined in this research. According to the investment and construction costs of offshore oil and gas production facilities in Japan (MH21, 2019), China (EIA, 2020) and the U.S.A. (EIA, 2020), the costs of production platforms and subsea systems have been estimated. Furthermore, a 10% additional cost has been incorporated for contingency, e.g., unexpected difficulty of construction and possible accidents.

Table 2 Increase/decrease rates of operating cost in different production stages in the basic model

Production stage	First 2/5	Intermediate 1/5	Last 2/5
Increaes/decrease rate	−20%	0%	10%

Table 3 Assumed reduction rates of tax in different production stages in the basic model

Production stage	First 1/5	Second 1/5	Third 1/5	Fourth 1/5	Fifth 1/5
Reduction rate	30%	20%	10%	0%	0%

Drilling cost is the product of the drilling and completion cost of a single well and the number of production wells. The drilling and completion cost per well is mainly influenced by the drilling depth and operational water depth. Based on the equations described in the Oil and Gas Supply Module (OGSM) for 2020 of the EIA (EIA, 2020), the drilling costs have been estimated for the three countries. The number of production wells affects not only capital expenditures but also gas sales revenue, which is an important factor in evaluating the economic critical resources and the economics of the project. Therefore, the economic critical resources change with the number of production wells are examined in Section 3.1.

The pipeline cost is calculated by multiplying the total length of the new pipeline by the construction cost per unit length. The length of the new pipeline is determined based on the investigation of existing pipelines in the three sea areas. Although most economic evaluations treat gas hydrate projects as stand-alone ventures, gas hydrates, like other resources, do not necessarily need to singlehandedly bear all the development costs required to enable their production. Gas hydrates occurring in existing petroleum provinces may be additional late-stage field development opportunities that utilize existing infrastructure (Boswell and Collett, 2011).

All production wells in the field have to be shut at the end of production life, resulting in a field abandonment cost. Following the method employed by EIA (EIA, 2020), the abandonment cost is set as a fraction of the initial platform cost.

As for operating expenditure (OPEX), because trial production was conducted over a short period, mainly to meet the scientific agenda, with less consideration for expenditure, it can only provide limited information with reference to the economic evaluation of NGH industrialization. The temperature and pressure differentials of the NGH production system are lower than those of deep conventional hydrocarbons. This is in contrast to conventional hydrocarbons that may have much higher temperatures, requiring substantial and costly handling, that induces higher levels of risk. So the drilling operation, flow assurance and environmental consequences of NGH exploitation will probably be easier to manage and therefore less costly (Max and Johnson, 2019). Therefore, it is reasonable to tentatively use the operating cost of offshore conventional gas as a rough estimate of the operating cost of NGH exploitation. Moreover, the 2% inflation rate and possible change rate of the operating cost over time have been considered in the calculation.

As the duration of gas hydrate production tests are still short, gas hydrate production-associated environmental damage and geological disasters were not encountered. The environmental risks of hydrate exploitation are still debated, with even the understanding of formation deformation during production still under study, so the associated costs could not be estimated. As a result, environmental costs have not been included in this study.

However, additional costs have been taken into account in the relevant production stages, such as insurance reserves during the well-site construction and drilling stage, with reference to the development experience of conventional oil and gas.

Due to different regulatory requirements and macro policies, the three countries have different tax policies for the oil and gas development industry (Table 4).

The natural gas price has an important effect on gas sales revenue. Assuming a scenario in which industrial exploitation is realized in the 2030s as stated in the Basic Plan on Ocean Policy formulated by the Japanese government, the gas production cost must be competitive against the LNG price at that time (MH21, 2019). With reference to the method published by MH21-S (MH21, 2019), the LNG price in Japan during the period 2030–2050 is estimated on the basis of the prediction of Henry Port's natural gas price of EIA. In China, the price of natural gas is guided by the government and is determined by the gate station price of natural gas in Guangdong Province (National Development and Reform Commission, 2019). The price of natural gas in the U.S. is derived from the Henry Port spot price, as predicted by the EIA (EIA, 2020). Since the Henry Port price for 2050–2059 is currently not available, the price during this period was extrapolated, based on the trend of natural gas prices from 2030–2050. However, the gas price should be within a certain range, due to the difficulty of predicting the supply and demand around the world. In Japan and the U.S., the volatility of gas prices is also considered. As the composition of hydrate gas is basically combustible gases (e.g., methane, ethane, and propane) (Max and Johnson, 2019), the commodity rate of the produced gas is assumed to be 98%.

Table 4 Tax rates for the oil and gas development industry in Japan, China and the U.S.A.

Country	Categories of taxes	Tax rate (%)	Reference
Japan	Income tax	31	(Minami, 2020)
China	Value-added tax	9	(Ministry of Finance et al., 2019)
	City maintenance and construction tax	7	(Sinopec, 2007)
	Educational surcharge	3	(Sinopec, 2007)
	Resource tax	4.2	(National People's Congress, 2019)
	Income tax	25	(Sinopec, 2007)
The U.S.	Royalty	18.75	(BOEM, 2020)
	Income tax	21	(BOEM, 2020)

3 Results and Discussion

3.1 Economic critical resources for industrial exploitation

The economic critical resources for commercialization of NGH in Japan, China and the U.S.A., changing with production life and the number of production wells, are summarized in Table 5. With the extension of production life, the economic critical resources required in the three countries increase, because more hydrates are needed to maintain the sustainability of long-term production and to ensure enough cash inflows in the later stages of the production. Over the same production period, the economic critical resources required in the three countries also increase when more production wells incur higher capital expenditure. It is inevitable that a higher gas production rate is required to bring more gas sales revenue to achieve profitability.

Under the same conditions of production life and the number of production wells, the economic critical resource required in China is the lowest, ranging from 3.62 to 24.02 billion m^3 of methane. Although the domestic natural gas prices in China and Japan are relatively high, resulting in lower economic critical resources, deepwater capital expenditure and operating costs in China are however, lower than those of Japan, due to the relatively cheap labor in China. According to the estimation of MH21–S (MH21, 2019), deepwater capital expenditure and operating costs in Japan are the highest among the three countries. Because domestic hydrocarbon resources are very limited in Japan, LNG has been imported for a long time. A high natural gas price enables Japan to realize the commercialization of NGH in the case of higher costs. Therefore, the economic critical resource required in Japan is larger than that in China, with an approximate range of 5.58–38.72 billion m^3 of methane. Although the deepwater capital expenditure and operating costs of the U.S. are lower than those of Japan, the natural gas price in the U.S.A. is much lower than in Japan and China, because of the impact of the shale gas revolution. Therefore, the natural gas sales market is highly competitive with limited profit margins in the U.S.A., necessitating higher gas production and economic critical resource of gas hydrate. The economic critical resource of NGH in the U.S. ranges from 9.31 to 44.28 billion m^3 of methane.

When it comes to the scale of hydrate reservoirs, GIP is a commonly used indicator. The conversion between GIP and economic critical resources requires the RF

Table 5 The economic critical resources for commercialization of natural gas hydrate, changed with production life and the number of production wells

Production life	5 years					10 years					15 years				
well	10	20	30	40	50	10	20	30	40	50	10	20	30	40	50
	Economic critical resources (billion m^3 methane)														
China	3.62	4.83	6.10	7.32	8.59	5.07	6.68	8.37	9.98	11.67	6.47	8.48	10.58	12.59	14.70
Japan	5.58	8.18	10.79	13.39	17.63	7.09	10.26	13.42	16.58	21.68	8.61	12.37	16.13	19.89	25.91
The U.S.	9.31	12.57	15.98	19.23	22.64	11.33	15.09	19.03	22.79	26.73	13.28	17.58	22.10	26.40	30.92
Production life	20 years					25 years					30 years				
well	10	20	30	40	50	10	20	30	40	50	10	20	30	40	50
	Economic critical resources (billion m^3 methane)														
China	7.86	10.27	12.80	15.21	17.74	9.26	12.08	15.05	17.87	20.84	10.69	13.94	17.35	20.60	24.02
Japan	10.05	14.39	18.74	23.09	30.01	11.52	16.48	21.44	26.40	34.26	13.05	18.65	24.25	29.85	38.72
The U.S.	15.18	20.04	25.16	30.02	35.13	17.13	22.60	28.34	33.81	39.55	19.21	25.32	31.75	37.86	44.28

estimation. This is typically determined from production experience; however, a lack of historical data and experience regarding gas hydrate production over extended periods leads to a very limited knowledge of RFs, that vary significantly with local geological conditions and reservoir quality. GIP change with RF is estimated as shown in Fig. 3. Obviously, the higher the RF, the lower the GIP required for industrial exploitation of gas hydrate. With an increase in RF, small-scale hydrate reservoirs originally considered sub-economic or marginal can also be economically developed. RF is not a fixed value and is highly dependent on technological development. As experience is gained and technology and science advance with time, RF will generally increase (Boswell and Collett, 2011). Additionally, technological advancement reduces costs. Therefore, for the industrial exploitation of hydrates, the most important consideration is to increase production and reduce costs through technological breakthroughs.

According to the results of the geological survey and the resource assessment of NGH, the estimated resources of the main target blocks of NGH reservoirs in the Shenhu area of the South China Sea are 150 billion m^3, the resources of the two large hydrate reservoirs being as high as 40 billion m^3 (He et al., 2020). Even with a recovery factor of 50%, such a large hydrate reservoir is sufficient for continuous production for 30 years (Fig. 3). In the eastern Nankai Trough, Japan, the value of the gas-in-place in the methane hydrate concentrated zones was estimated at 176.9 billion m^3, in the 90% confidence intervals of the probability density function for a Monte Carlo simulation. The resources of the three identified methane hydrate concentrated zones are 8.7, 11.1, 59.1 billion m^3, respectively (Yamamoto, 2022). These hydrate reservoirs all meet the threshold of industrial exploitation, but at the same recovery factor, larger hydrate reservoirs can be exploited for a longer term (Fig. 3). With the improvement of recovery factor and the reduction of

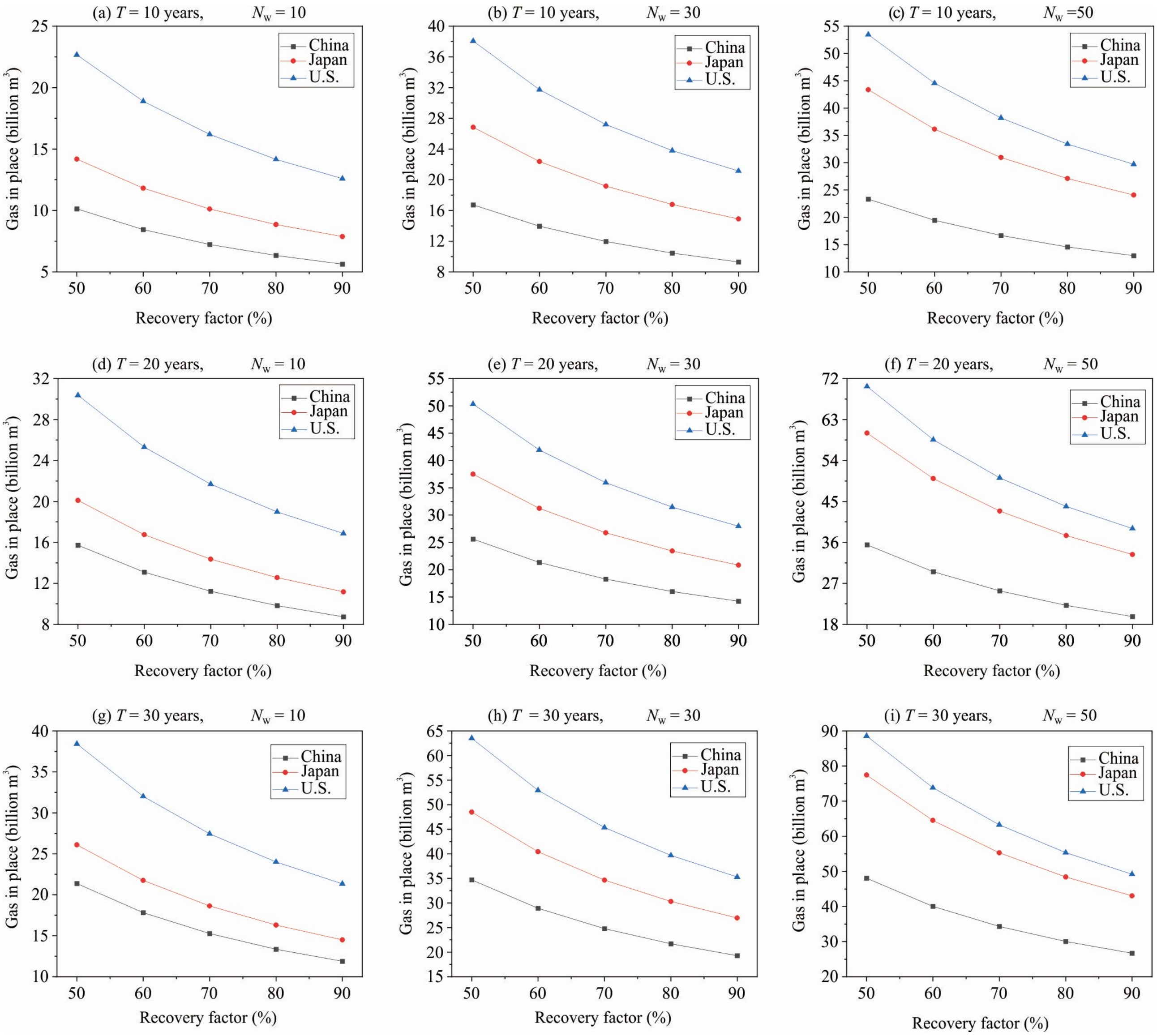

Fig. 3. GIP of commercialization of natural gas hydrate, modified with recovery factors.
T and N_w denote production life and number of production wells, respectively.

production costs, more and more gas hydrate reservoirs will meet the resource requirements for industrial exploitation. The prospect of industrial exploitation of natural gas hydrate might not be that far from realization.

3.2 Sensitivity analysis

Economic critical resource is determined by the interaction of cash inflows and outflows during the life cycle of a hydrate reservoir. The change in natural gas price is the most important parameter affecting cash inflows, while the number of production wells, decreasing rate in operating cost and tax incentives are the most critical parameters affecting cash outflows. Sensitivity analysis is conducted to provide a better understanding of the effect induced by these critical parameters on economic critical resources. As the results for Japan are based on the data from long-term research on the industrial exploitation of NGH by MH21–S and those of China and the U.S. are based on the extension of the cost of offshore conventional natural gas, it is more reasonable to take Japan as an example for discussion, rather than China and the U.S.A..

The changes in economic critical resource for NGH commercialization with the number of production wells are shown in Fig. 4. As mentioned above, longer production periods or more production wells require a larger economic critical resource. It is worth noting that the value range of economic critical resource corresponding to a shorter production period is smaller based on the assumption that all wells are drilled during the construction period (prior to production). When the same number of wells are planned, the present value of the cash outflow caused by well construction is the same. These cash outflows need to be compensated by producing more gas to achieve higher gas sales revenue. Assuming the annual production is constant, the present value of cash inflow generated each year becomes lower and lower over time. Therefore, the longer the production period, the higher the gas production rate, and the greater the economic critical resource.

Additional wells induce more drilling costs but can increase gas production. Moreover, more production wells result in a cost reduction in infrastructure (e.g., platforms and pipelines) that all wells can share. The break-even production for a single well will decrease with the increasing number of wells at first. However, when the number of wells reaches a certain limit, such as 48 wells in this model, the break-even production per well reaches a local minimum. Because once the number of wells exceeds the threshold, new platforms are needed or the platform scale needs to be greatly expanded to support the operation of these additional wells. From a financial point of view, there is an optimal number of wells for any given NGH exploitation project.

With the changes in the supply and demand of natural gas and other energy forms, the future of the natural gas market is full of uncertainty. Therefore, it is reasonable to consider natural gas price fluctuations on the basis of the basic model. Fig. 5 shows the impact of natural gas price fluctuations on the economic critical resource for NGH exploitation in different production lifespans. The economic critical resource is negatively correlated with the natural gas price. Natural gas prices used in the basic model ($P_{g,b}$) are predicted with a range from 0.34 to 0.51 $/m^3. If the actual price of natural gas in the future goes down, the economic critical resources for different production lifespans increase significantly. When the natural gas price is 2$P_{g,b}$ (0.68–1.02 $/m^3), the economic critical resource drops from 15.5–34.3 to 6.7–13.0 billion m^3 of methane. When the gas price changes from 0.3$P_{g,b}$ (0.10–0.15 $/m^3) to 3$P_{g,b}$ (1.02–1.53 $/m^3), the reduction multiples of the economic critical resources for different production lifespans are all greater than 10 times (14.5–45.4 times). Apparently, the economic critical resource is

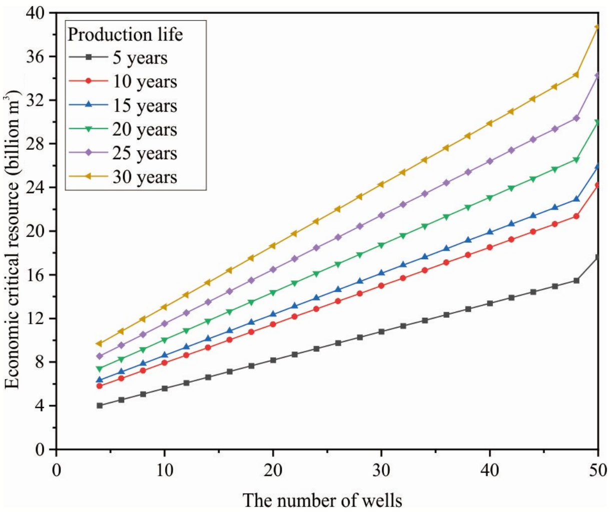

Fig. 4. Sensitivity analysis of the number of wells on economic critical resources for NGH commercialization over different production lifespans, evaluated when the discount rate used to determine the present value of future cash flows is 10%.

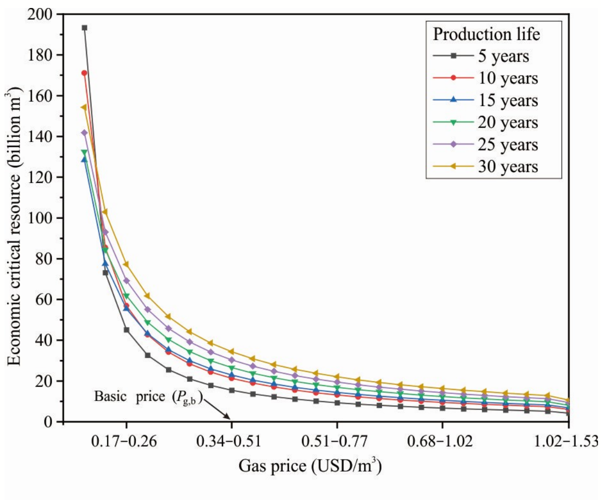

Fig. 5. Sensitivity analysis of the fluctuation of gas price on economic critical resources for NGH commercialization over different production lifespans, evaluated when the discount rate used to determine the present value of future cash flows is 10% and the number of wells is 48.

highly sensitive to future gas prices.

With the accumulation of production experience and the improvement of technology, the operating cost will usually drop to a certain extent in the initial stage of production. On the other hand, the energy resources in the reservoir will experience natural decay during production life. The amount of resources that can be easily recovered will reduce over time. More investment will be required to recover the same amount of resources. When technical progress interacts with resource depletion, operating costs will first decrease and then increase (Dale et al., 2012). In this research, the decreasing rate in operating cost is used to reflect the effect of technological progress. The impact of different decreasing rates in operating cost on economic critical resource for NGH exploitation is described in Fig. 6. Over various production lifespans, economic critical resource has shown a downward trend with the reduction of operating costs. However, the sensitivity of economic critical resource to the reduction of operating costs is lower than those of natural gas prices and the number of production wells, which is caused by the model assumptions that (a) operating costs decrease only in the first 2/5 production life due to technological progress, and (b) operating costs increase at a constant growth rate in the last 2/5 production years. Therefore, the cost reduction resulting from technological progress makes only a limited economic contribution to the NGH exploitation project.

NGH exploitation from domestic reserves helps to make the country more energy self-sufficient by reducing dependence on imports (Oyama and Masutani, 2017). In light of this, some governments with very limited domestic hydrocarbon resources may provide tax incentives or even tax subsidies to stimulate the industrial exploitation of NGH. Favorable tax policies enhance the economics of gas hydrate exploitation projects and have generated positive incentives for producers (CEFM, 2019). Reducing corporate income tax is a common tax incentive policy. In this research, it is assumed that within the time span of the first, second and third 1/5 of production life, the income tax is reduced or exempted at a set of percentages, respectively. Fig. 7 shows the economic critical resource impacted by different combinations of corporate income tax reduction rates in different production periods. As the income tax reduction rate increases, economic critical resource gradually decreases. If the tax reduction rate is the same, the economic critical resource in a longer production period decreases more, because the producers can receive a greater absolute value of the tax incentive in the longer period.

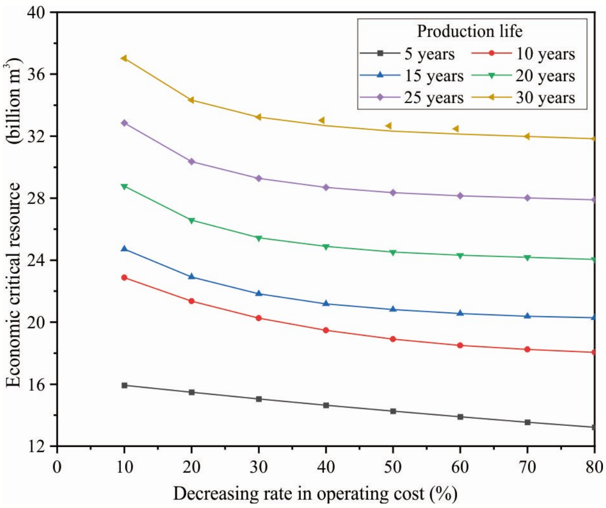

Fig. 6. Sensitivity analysis of the decreasing rate in operating cost on economic critical resources for NGH commercialization over different production lifespans, evaluated when the discount rate used to determine the present value of future cash flows is 10% and the number of wells is 48.

4 Conclusions

In this research, the economic critical resources for industrial exploitation of natural gas hydrate (NGH) over different production lifespans, considering several key factors, such as the number of production wells, gas price, technological improvement and tax incentives, were estimated, based on the net present value (NPV) method, the following conclusions being obtained:

(1) The economic critical resources for industrial exploitation of NGH in the three countries of Japan, China, and the United States (U.S.A.) were estimated. Compared with the U.S.A., the relatively low economic critical resources required in China and Japan are 3.62–24.02 and 5.58–38.72 billion m^3 methane, respectively. NGH is most likely to be profitably recovered in countries that rely on natural gas imports (Milkov and Sassen, 2002).

(2) With improvements in recovery efficiency, small-scale hydrate reservoirs originally considered sub-economic or marginal can also be economically developed. Therefore, technological improvement, which

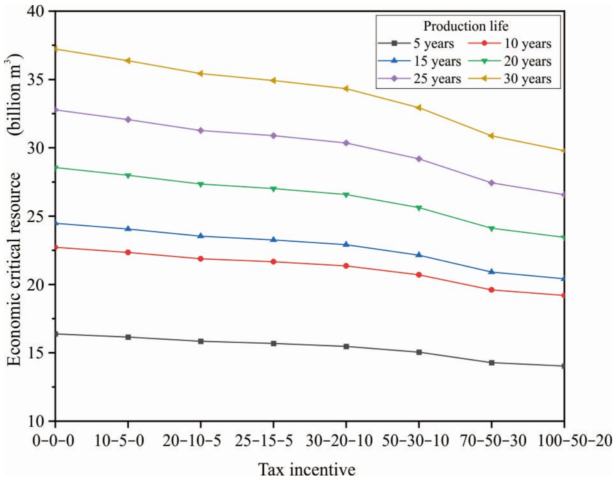

Fig. 7. Sensitivity analysis of tax incentive on economic critical resource for NGH commercialization over different production lifespans, being evaluated when the discount rate used to determine the present value of future cash flows is 10% and the number of wells is 48.

The three numbers per set shown in the *x*-axis represent three reduction rates in income tax during the first, second and third 1/5 of production life, respectively. For example, 10-5-0 indicates the reduction rates in income tax are 10%, 5%, and 0% during the first, second and third 1/5 of production life, respectively.

is the most critical factor in enhancing recovery efficiency, is key to the industrial exploitation of NGH.

(3) Natural gas price is the most significant factor that affects the economic critical resource of NGH. Higher natural gas prices improve the economic feasibility of gas hydrate exploitation (Milkov and Sassen, 2002), leading to lower economic critical resource.

(4) Tax incentives can promote the industrial exploitation of NGH, which may depend on the authority's consideration of energy security and environmental factors.

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