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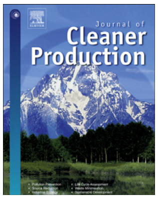

Estimation of China's production efficiency of natural gas hydrates in the South China Sea

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ABSTRACT

Natural gas hydrates are expected to be one of the most important unconventional energy resources in the future. China is accelerating its research and trial exploitation of hydrates in the South China Sea, which is where most of China's gas hydrate reservoirs are located. Because it represents a prospective alternative energy source, it is necessary to use the energy return on investment method to evaluate production efficiency. The results show that the average standard energy return on investment is 0.74, the energy return on investment within the boundary from wellhead to processing is 0.58, and the energy return on investment within the boundary from well to utilization is 0.56. The negative net energy suggests that natural gas hydrate is not presently a favourable choice to replace conventional energy sources; thus, the large-scale development of natural gas hydrate requires further technological development. Sensitivity analysis shows that to acquire a strong positive energy return on investment, technological developments must be accompanied by simultaneous increases in ultimate gas recovery and the gas-to-water ratio. Moreover, the choice of proper production methods has an important influence on energy return on investment and should be based on the knowledge of physical properties gained through sufficient geological surveys.

1. Introduction

According to the International Energy Outlook report, the world energy consumption is expected to reach 20,679 million tons of oil equivalent in 2040, with conventional fossil fuels continuing to supply approximately 80% of the demand (Vedachalam et al., 2015, 2016). With increasing concerns regarding climate change, natural gas is expected to be an important alternative to coal as well as a transitional fuel for variable renewable energy sources, such as wind and solar (Anwar, 2016). The world's gas demand continues to increase and is expected to reach 5.23 trillion cubic metres (tcm) in 2040 (Vedachalam et al., 2016). With the depletion of conventional gas resources, the importance of exploration of unconventional gas resources is increasing. Since natural gas hydrate (NGH), an unconventional natural gas, has a carbon quantity twice that of the world's proven fossil fuels (Chong et al., 2016), it has attracted increasing global attention. NGH reserves distributed around the world amount to approximately 2×10^4 tcm (Aghajari et al., 2018). As a result, many countries, e.g., the U.S., Japan, Canada and China, have implemented their own commercial NGH production schedules (Lu, 2015; Ding et al., 2017).

Currently, China leads the development of the world's NGH mining technology. Total NGH reserves in China are approximately 84 tcm, mainly distributed in the East China Sea (3.38 tcm), South China Sea (64.96 tcm), Qinghai-Tibet Plateau permafrost (12.5 tcm), and Northeast China permafrost (2.8 tcm) (Tan et al., 2016). The South China Sea is the key area for NGH prospecting (Tan et al., 2016). On July 9, 2017, the Shenhu area successfully completed a 60-day NGH production test and produced more than 300 thousand cubic metres of gas, representing world records in terms of both time span and cumulative production (MLRC, 2017). On November 3, 2017, the Chinese government approved NGH as a new mineral, becoming the 173rd mineral species in China (Xinhuanet, 2017). It is foreseeable that China will accelerate research on NGH development, and the South China Sea will be the

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Nomenclature

Acronyms

CNG	Compressed natural gas
EROI	Energy return on investment
FLNG	Floating liquefied natural gas
LCA	Life-cycle assessment
NGH	Natural gas hydrate
PTU	Processing-to-use
UGR	Ultimate gas recovery
WTP	Well-to-processing

Symbols

C_{platform}	The offshore platform investment for a well per year ($/yr)
C_{drilling}	Total drilling monetary cost ($)
C_{diesel}	The cost of purchasing diesel ($)
D_{well}	The well depth (m)
E_t^O	The energy output from time t-1 to t, and
E_t^I	The energy input from time t-1 to t
EROI_t	Time-series EROI
EROI_L	Life-cycle EROI
$\text{EROI}_{\text{stnd}}$	Standard EROI
$\text{EROI}_{\text{proc}}$	EROI within the boundary from well to processing
EROI_{use}	EROI within the boundary from well to utilization
E_{out}	The UGR in the life-cycle of a well
E_1	Energy investment in preparation
E_2	Energy investment in drilling
E_3	Energy investment in drainage exploitation
E_4	Energy investment in WTP transportation
E_5	Energy investment in processing
E_6	Energy investment in PTU transportation
EI	The energy intensity of an economy (MJ/$)
h_{electric}	The heating value of electricity (MJ/kWh)
h_{diesel}	The heating value of diesel (MJ/kg)
I_{pump}	The effective power of the electrical submersible pump ($\text{kWh/m}^3\bullet\text{m}$)
I_{disposal}	Unit energy consumption for water disposal (MJ/m^3)
L_a	Gas losses during WTP transportation
L_b	Gas losses during processing
L_c	Gas losses during PTU transportation
M_{diesel}	The annual diesel consumption of a well (kg/yr)
M_{water}	The amount of water (m^3)
R_{diesel}	The daily average diesel consumption (kg/day)
T_{drilling}	The drilling time (days)
t	The production period of oilfields (or gas fields)
T	The life-cycle span of a well (yr)

key area for future exploitation.

In addition, abundant gas hydrates have been discovered in the North Bay, Xisha Trough and Shenhu areas of the South China Sea (Liu et al., 2016). Currently, numerous studies on NGH, gas production methods, numerical and experimental simulations of gas production, and field trials have been conducted by various research groups around the world (Li et al., 2016). However, the production efficiency of NGH, as an important topic, has been studied only minimally.

Energy return on investment (EROI) analysis, which reflects the amount of energy that can actually be delivered, is a useful approach for assessing the production efficiency of an energy source (Hu et al., 2011; Murphy et al., 2011; Gupta and Hall, 2011). To date, however, the peer-reviewed literature contains scant results regarding the EROI of NGH production. This study takes the survey area in South China Sea as the subject to analyse the EROI of NGH wells. Determining the EROI value requires accurate and detailed data, the most important of which is the ultimate gas recovery (UGR) at wellhead and energy inputs in each process (Chen et al., 2015). To date, a series of drilling programmes, field surveys, and production numerical simulations have been performed sequentially regarding the NGH in the South China Sea (Sun et al., 2017), providing a foundation for EROI analyses. Here, this paper first collects the data of three main prospected sites in the South China Sea from the existing literature and then calculates the standard EROI ($\text{EROI}_{\text{stnd}}$), EROI within the boundary from well to processing ($\text{EROI}_{\text{proc}}$), and EROI within the boundary from well to utilization (EROI_{use}). In addition, sensitivity analyses, including UGR and gas-to-water ratio, are performed. The EROI results of this paper will provide valuable suggestions for NGH development in the South China Sea.

The paper proceeds as follows. Section 2 explains the EROI methodology. Section 3 explains the data on NGH energy outputs and inputs. Section 4 analyses the EROI results. The final section provides a discussion.

2. Literature review

The concept of EROI was first proposed by Hall et al. in 1981 (Hall et al., 1981). Since then, the EROI has been widely used, particularly in fossil energy production. The use of EROI is a new approach to evaluate energy production physically rather than purely monetarily (Cleveland et al., 1984; Cleveland, 1992). Compared with monetary assessments, EROI has some advantages in assessing energy production. First, energy is the foundation of socio-economic development. In the context of the shortage of energy resources, we should explain how much energy resources can be provided for human development. Therefore, it is one-sided to consider energy production activities only from an economic perspective (Hall et al., 1986). Second, according to an ecological perspective, the value of natural resources cannot be measured in terms of money, because the circulation of money in human society does not pass through nature, and money is only a means of assessing economic activity (Odum, 1996). Third, EROI assesses the efficiency of energy production and is considered one of the most suitable methods of net energy analysis (Gilliland, 1975; Cleveland et al., 1984). It uses ecology to understand the net energy, which considers the true value of all organic matter and society as a whole (Odum, 1971; Hall, 1972).

The mainstream protocol in EROI analysis was proposed by Murphy et al. (2011). Prior to this, the methodologies on EROI were divergent. In particular, published values of EROI for similar fuels are sometimes significantly different caused by using different boundaries and variables (Hu et al. 2013). In 2011, a two-dimensional framework for EROI analysis was proposed by Murphy et al. (2011), which is widely recognized and used by scholars. The proposed framework included several boundaries, where different factors are included, which allows researchers to state which EROI they are referring to in their calculations.

In the past, the EROI method was mainly used to analyse conventional oil and gas such as Hall et al. (1981), Cleveland et al. (1984), Hall et al. (1986), Cleveland (2005), Gately (2007), Gagnon