Energy Economics 42 (2014) 355–364

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

The economics of exploiting gas hydrates ☆

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ARTICLE INFO

Article history:
Received 11 March 2013
Received in revised form 31 October 2013
Accepted 2 November 2013
Available online 19 November 2013

JEL classification:
Q32
Q54

Keywords:
Exhaustible resources
Double externalities
Greenhouse gases
Methane hydrates

ABSTRACT

We investigate the optimal exploitation of methane hydrates, a recent discovery of methane resources under the sea floor, mainly located along the continental margins. Combustion of methane (releasing CO2) and leakage through blow-outs (releasing CH4) contribute to the accumulation of greenhouse gases. A second externality arises since removing solid gas hydrates from the sea bottom destabilizes continental margins and thus increases the risk of marine earthquakes. We show that in such a model three regimes can occur: i) resource exploitation will be stopped in finite time, and some of the resource will stay in situ, ii) the resource will be used up completely in finite time, and iii) the resource will be exhausted in infinite time. We also show how to internalize the externalities by policy instruments.

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1. Introduction

Alongside conventional fossil fuels, notably oil, coal, and natural gas, a new source of natural gas discovered in the last few decades has moved into the focus of interest: the so-called gas hydrates. These are solid crystalline compounds of gas and water molecules in which a guest gas molecule, notably methane (CH4), is trapped in a cage structure formed by water molecules. For its formation, methane hydrate, by far the most frequent form of gas hydrates on earth, requires both ample amounts of the fermentation gas CH4 and sufficiently low temperatures and high pressure conditions. Accordingly, their occurrence is limited mainly to the Arctic permafrost regions and oceanic sediments where gas hydrates occur especially on the continental margins. The methane hydrate stability zone starts at water depths of 100 m; the higher the temperature, the deeper the boundary of the stability zone. This is why methane hydrates can never survive on the surface of the earth (e.g. Bohrmann and Suess, 2004).

Due to these restricted stability conditions, a temperature increase of only a few Centigrade caused by global warming could destabilize gas hydrate deposits (Krey et al., 2009). This would have a twofold impact. As gas hydrates act as a kind of cement in the porous sediments of the continental margins, their destabilization would entail geological risks possibly even extending to eruptive sediment failure. These in their turn can cause tsunamis (Max, 2003). Furthermore, CH4, a more powerful greenhouse gas than carbon dioxide (CO2), would be released either into the atmosphere or into the ocean.

Due to slow response times of deep ocean temperatures to surface temperatures (100–1000 years), CH4 is mostly released chronically from deeper ocean deposits. Accordingly, CH4 does not reach the atmosphere as methane but oxidizes in the ocean to CO2 (Archer, 2007). Only in the case of catastrophic blowouts CH4 is capable of reaching the atmosphere. By contrast, methane hydrate deposits on the shallow arctic shelf and hydrates widespread in the permafrost regions are more vulnerable to temperature change. Hence, in these areas there have been observations of CH4 being released into the atmosphere. For this reason, (Max, 2003) propose cautious “preventive exploitation” of dissolving methane hydrates to mitigate the escape of CH4 into the atmosphere and its impact on climate.

Currently, geoscientists and engineers all over the world are engaging in research activities geared to extracting methane from gas hydrates in a cost-efficient way and avoiding too much methane leakage during this process. This research interest is further motivated by the tremendous amounts of CH4 stored in the hydrates and by its geographically widespread distribution. For example, Kvenvolden (1988) estimates that there are 10,000 gigatonnes (Gt) of carbon stored in methane hydrate deposits. This corresponds to twice the amount of currently recoverable worldwide fossil fuels (Sloan and Koh, 2008) and has been the most-widely cited “consensus value” over the last few decades. However, (Milkov, 2004) has updated the global estimate of hydrate-bound gas to a value of ~500–2500 Gt of methane carbon in a calculation that best

☆ We would like to thank Rolf Farnsteiner and Detlef Müller from the Mathematical Department of Kiel University for helping us in solving several mathematical problems, and Klaus Wallmann from GEOMAR for introducing to us in detail the physics and chemistry of gas-hydrates. We also thank two anonymous referees for their helpful suggestions to improve an earlier version of this paper.

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http://dx.doi.org/10.1016/j.eneco.2013.11.001

reflects current knowledge on submarine gas hydrates. Even if only a small fraction of these energy resources was technically and economically exploitable, methane from sea-floor gas hydrates could play an important role in the world's energy mix, as already one promille of the estimated global methane hydrates inventory would cover current annual global energy needs (Walsh et al., 2009).

In terms of the final product, gas extracted from gas hydrates is a close substitute for natural gas. One major difference is that natural gas contains up to 20% other hydrocarbons and inert gases, while gas extracted from methane hydrates is almost pure CH4, the chemically most stringently reduced form of carbon. Of all hydrocarbons, CH4 is the least carbon-intensive, so energy from CH4 produces the lowest quantity of CO2 per unit of output.

To the best of our knowledge, (Walsh et al., 2009) were the first to mention gas hydrates in an economic journal. In their paper, they sum up recent research on the resource potential of gas hydrates and estimate the gas prices at which the exploitation of gas hydrates would become profitable. They find that gas prices of around 7–12 $US/Mscf (US dollars per thousand standard cubic feet) would be necessary to cover the costs involved in exploiting terrestrial hydrate deposits. For marine hydrates, the costs of extraction would be 3.5–4 $US/Mscf higher than for a comparable offshore deposit of conventional natural gas. In the context of offshore extraction, the authors also mention "another level of risks which cannot yet be quantified" (p.821), which we interpret as the geological risk associated with extraction of offshore hydrates.

Economically, the discovery of gas hydrates may be beneficial for the world economy, as a) it may reduce the scarcity of fossil fuels, in particular of natural gas, and b) as a low-carbon source of energy it can serve as a transition to zero-emission energies. Countries with access to sea-floor resources according to Art. 77(1) UNCLOS, such as Norway, Russia, India, USA, China, Japan, New Zealand, Chile, and possibly others, will benefit from exporting methane, but importers will also benefit from lower gas prices on the world market. On the other hand, the prospect has its drawbacks, since exploitation of gas hydrates may give rise to two kinds of externalities. First, even "preventive methane exploitation" from gas hydrates contributes to global warming in two different ways, a) by combustion and hence generation of CO2, and b) by methane leakage during the mining process. Second, mining of the hydrates, i.e. removal of the "cement", may also lead to the destabilization of continental margins, and this may increase the risk of marine geohazards.

In this paper we present a model that addresses these two problems and the ongoing dissolution of the hydrates. The simple model has Arctic methane hydrates as the only exhaustible resource whose stock is not only reduced by extraction but also by dissolution. We then assume that economic damage is generated by a) accumulation of greenhouse gases, and b) by the risk of marine earthquakes. To keep the model simple, we do not directly model substitutes for methane hydrates. However, we account for them in an indirect way by assuming that there is a finite choke price on the demand side.

Our paper draws on the literature that links the exploitation of non-renewable resources to the externalities caused by releasing greenhouse gases, e.g. Ulph and Ulph (1994), Tahvonen (1997), Hoel and Kverndokk (1996), and Farzin and Tahvonen (1996). Except for the latter, these studies all assume complete recreation capability of the atmosphere modeled by linear decay of the pollution stock. Therefore the pollution externality impacts on the timing of extraction but does not affect the amount extracted, and the resource stock is asymptotically reduced to a certain level when extraction costs are sufficiently high. The main conclusion from this literature is that an optimal emission tax may be non-monotonic, increasing in the first stage and decreasing in the final stage. Furthermore, our paper is related to studies with a focus on resource scarcity and environmental constraints. For instance, Farzin (1992, 1996) and Krautkraemer (1998), provide the basics for interpreting the shadow values of resource extraction and greenhouse gas emissions in our model. Since the expected damage from geohazards depends on the remaining resource stock and therefore assigns a value to a positive stock level, our model also relates to Krautkraemer (1985) and Beltratti et al. (1994), who account for an amenity value of the resource stock.

In our paper we characterize the socially optimal exploitation paths for a resource stock of methane hydrates. With the ongoing natural dissolution of the (methane hydrate) resource stock, it is not possible to maintain a positive economically worthwhile stock of the resource. Instead, the resource stock will inevitably vanish as time goes to infinity. This circumstance drives our main findings. If the choke price is sufficiently low compared to overall social costs, in a social optimum some of the resource will be left in situ and extraction will not only approach zero but actually will be zero at some point in time.

If, by contrast, the choke price exceeds these overall social costs, the well-known Hotelling solution will apply, i.e. the resource will be used up completely in finite time. Only in the case where the two magnitudes are equal can the standard result of stock-externality models be maintained, i.e. the resource will be reduced to zero in infinite time, and extraction rates – though small – will remain positive for all time. We also look at optimal policies for decentralizing the first-best outcome. We show that this can be done by charging a single tax on resource extraction that accounts for both stock externalities.

Our paper is organized as follows: In Section 2 we describe our model and set up the optimality conditions before characterizing the optimal solutions in Section 3. In Section 4 we further investigate the optimal exploitation path employing specific functional forms and show some examples of possible extraction/emission paths. In Section 5 we study decentralization of the first-best exploitation path. The final section concludes.

2. The model

We consider a model where consumers draw utility from consuming a non-renewable resource referred to as methane hydrates. We ignore the fact that there are other fossil fuels as substitutes. We use x_t to denote the resource stock and q_t to denote the quantity of methane hydrates extracted at time t.

In addition, the atmospheric release of methane from the dissolution of hydrates – either chronically or by blow-outs – is modeled as a rate of natural leakage and is denoted by $\beta \geq 0$. In other words, at each point in time, a share βx_t is naturally converted from the stock of methane hydrates and released as methane gas into the atmosphere. Thus the equation of motion for the stock of methane hydrates is

$$x_t = -q_t - \beta x_t. \tag{1}$$

Under pre-industrial conditions, the stock of gas hydrates located in the so-called gas hydrate stability zone was by and large in a steady state. New hydrates were formed from particular organic carbon (POC) (see Wallmann et al. (2012)), while at the same time a certain share was dissolved in the ocean. According to (Biastoch et al., 2011), there is evidence that due to ocean temperature rise the share of dissolving methane hydrates currently exceeds the share being renewed through POC.[1] In Section 3 we will also discuss $\beta = 0$ as a special case. In a more sophisticated approach one could model the natural leakage rate as a function of temperature and thus as a function of the stock of greenhouse gases in the atmosphere. In this paper we abstain from doing so, since it would make the model intractable.

Furthermore, we assume that extraction causes some leakage, as it has been impossible so far to develop an extraction technology that works free of leakage. This is modeled by a share ζq_t that can be consumed, while a share $(1 - \zeta)q_t$ of the methane hydrate is irreversibly lost and diffuses as methane gas into the atmosphere.

[1] The authors estimate that about 12% of the world's gas hydrates will be lost within the next century. With a constant rate of decay, this indicates a positive $\beta \approx 0.00555$.

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