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Modeling peak oil and the geological constraints on oil production

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ABSTRACT

We propose a model to reconcile the theory of inter-temporal non-renewable resource depletion with well-known stylized facts concerning the exploitation of exhaustible resources such as oil. Our approach introduces geological constraints into a Hotelling type extraction–exploration model. We show that such constraints, in combination with initially small reserves and strictly convex exploration costs, can coherently explain bell-shaped peaks in natural resource extraction and hence U-shapes in prices. As production increases, marginal profits (marginal revenues less marginal extraction cost) are observed to decline, while as production decreases, marginal profits rise at a positive rate that is not necessarily the rate of discount.

A numerical calibration to the global oil market predicts substantially higher future oil prices and considerably lower global oil production with the more realistic geological constraints set-up than with the Hotelling simulation. While mainly (small) non-OPEC producers increase production in response to higher oil

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prices induced by the geological constraints, most (large) producers' production declines, leading to a lower peak level for global oil production. High future oil prices therefore, do not necessarily translate to increased oil supplies on global markets.

1. Introduction

Nonrenewable resource models of the Hotelling (1931) tradition are powerful tools for examining how economic and physical variables may interact, thus influencing production and price profiles. The characterizing feature for such models is the optimal inter-temporal depletion of a stock of non-renewable resource. The original non-renewable resource depletion model proposed by Hotelling (1931), which also still happens to be the standard economic model in the field, predicts that as a non-renewable resource is depleted, production (price) declines (rises) monotonically and marginal profit rises at the rate of discount. These predictions are, however, at odds with: firstly the observed stylized facts regarding quantity and price paths that (i) regional and aggregate nonrenewable resource production profiles usually exhibit bell-shaped peaks, and that (ii) nonrenewable resource prices tend to follow U-shapes; secondly, the result that marginal profits rise at the rate of discount has so far received little empirical support from the data despite researchers' best efforts (cf. Slade and Thille, 2009; Livernois, 2009; Krautkraemer, 1998; Chermak and Patrick, 2002).

This article proposes a simple model to reconcile the economic theory of non-renewable resource depletion with the above mentioned stylized facts. While some of the literature (cf. Holland, 2008; Livernois and Uhler, 1987; Campbell, 1980; Slade, 1982; Pindyck, 1978) attempts to reconcile this theory with the outlined empirical facts, none consider the contribution of geological constraints.[1] At the same time, those that introduce geological constraints (e.g., Cairns and Davis, 2001; Nystad, 1987; Thompson, 2001), focus on the single reserve case (i.e., the intensive margin of resource exploitation) and deal with different issues than those that are of interest in this article. For example, Cairns and Davis (2001) formalizes Adelman's hypothesis on why producers value the stock of in-ground reserves at about half the value given by the Hotelling valuation principle; Nystad (1987) seeks to explain why geological constraints imply lower initial production levels; and Thompson (2001) seeks empirical support that the valuation principle for a stock of in-ground reserves predicted by the geological constraints model fits better to the data than the Hotelling valuation principle.

As emphasized in the oil engineering literature (e.g., Ahmed, 2010; Arps, 1945), geological constraints as dictated by physical reservoir characteristics and pressure within the reservoir limit the amount of oil a producer can extract at any moment in time. To overcome such constraints, the producer might be induced to explore for new reserves at the extensive margin so as to increase production at the intensive margin. Nonetheless, since resources are ultimately limited, aggregate production may increase only for a while before declining. Such a view of increasing and subsequently declining oil production, due to the impacts of geological constraints, is the backbone for curve-fitting peak oil models like the Hubbert (1962) model that predominate the technical literature (cf. Berg and Korte, 2008; Kaufmann, 1991; Pesaran and Samiei, 1995; Mohr and Evans, 2007). The shortcoming of such technical models, however, is that because production is constrained to trace a pre-specified mathematical curve, there is no straightforward means of introducing economic variables. As such, curve-fitting models are generally of limited use for understanding how economics and geological constraints can interact to shape production profiles and the corresponding economic variables such as price.

The objectives of this article are twofold. First, to theoretically investigate how geological constraints for pressure produced resources integrated into a Hotelling-type model can alter the producer's optimal extraction decision under divergent assumptions about reserve size and cost. We

[1] For oil and natural gas that are of main concern in this article, such constraints are the pressure within the reservoir and the reservoir characteristics such as the porosity and permeability of the producing rock.