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On equilibrium in resource markets with scale economies and stochastic prices

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ABSTRACT

In this paper, I show the existence and the characteristics of equilibrium in a non-renewable resource market where extraction costs are non-convex and market price is subject to stochastic shocks, an empirically relevant setting. In my model firms may be motivated to hold inventories to facilitate production smoothing, which allows them to continue producing at a smooth pace at any instant when extraction ceases, *e.g.* when reserves are exhausted. This aspect of the model then supports a competitive equilibrium in the presence of non-convex costs. Casual empirical evidence is provided that supports the central features of my model for a variety of non-renewable resources, lending credence to the explanation for equilibrium I propose.

1. Introduction

Scale economies in production appear to be an important phenomenon for many non-renewable resources. These economies can be manifested in the presence of persistent fixed costs, for example when there are irretrievable investments in mining capacity, or because of efficiencies obtained by expanding existing mines. In either event, average costs would be U-shaped. The empirical relevance of scale economies has been well-documented for a variety of resources [10,22,30].

The presence of non-convex costs is important because of the potential effect they may exert on the equilibrium price path. Indeed, Eswaran et al. [14] (hereafter, ELH) have argued that non-renewable resource markets where production is characterized by non-convex costs need not support a competitive equilibrium. The spirit of their argument is that an equilibrium must entail firms extracting at a rate which intertemporally equates rents (*i.e.*, firms follow the [18] "r-percent rule"); firms who follow such a program will discontinuously change production at some terminal time, reducing their extraction rate from that which minimizes average cost (where average cost equals marginal cost) to zero. With discontinuous changes in extraction there would be a jump discontinuity in price. But the firm could then increase their present discounted value by delaying the exhaustion of its reserves, upsetting the putative equilibrium strategy.[1]

ELH's gloomy message appears to be at odds with the observation that there are well-functioning markets for both current and future delivery of a large variety of non-renewable resources. Their non-existence result could be reconciled with the empirical evidence in a variety of ways. For ELH's argument to go through, one must rule out "chattering controls", whereby firms instantaneously switch between producing nothing and producing some positive level, thereby

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[1] A number of other papers have further investigated the implications of non-convex production costs for competitive equilibria in markets for non-renewable resources; examples include Oleweiler [24], Eswaran et al. [14], Hartwick et al. [17], Cairns [7], Asheim [3], Lozada [20] and Fisher [16].

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convexifying their problem.[2] So the first reconciliation of the ELH result with apparently well-functioning resource markets is that chattering controls can not be ruled out. A second explanation is that the production of these resources is not subject to non-convex costs. Third, agents might not employ rational expectations. Fourth, perhaps there is a backstop technology with cutoff price at or below the terminal price in the optimal program outlined above. Fifth, strategic considerations might be underlying current behavior, with such behavior being part of a non-cooperative equilibrium [7,3,15].

In my view, none of these explanations is very palatable as a broad explanation. The empirical relevance of chattering controls seems questionable because it is generally costly to close down and re-open a mine or production well. Anecdotal evidence supporting this point can be found in the U.S. Natural Gas market: for most of 2002 and 2007 the spot prices of Natural Gas at trading hubs in the state of Wyoming were well below the trading price at Henry's Hub (generally thought of as the benchmark for the U.S. market); in 2007, this differential was often in the range of $4 per mcf, roughly 80% of the spot price at Henry's Hub. In both years, the differential was widely regarded as resulting from insufficient pipeline capacity leaving the state of Wyoming, and in both years the price differential disappeared following pipeline capacity expansion. As a result, it seems reasonable that agents would have anticipated sharp increases in spot prices at Wyoming trading hubs as the new capacity was being built in 2007. But most Wyoming producers elected to leave their wells in continual operation during 2007, typically claiming that the cost of 'shutting in' production would be unacceptably large. The fact these producers were willing to forego what were likely to be significant increases in revenues suggests that there were in fact important costs associated with making discrete changes to extraction rates (either in shutting off production or in restarting it). The hypothesis that agents are simply myopic, or dumb, is facile. Similarly, it is hard to believe that, serendipitously, a cutoff price for a backstop just happens to prevent a jump in prices when firms' reserves tap out. Appealing to a non-cooperative framework may have appeal for some resources, but many markets for natural resources are characterized by large numbers of firms extracting firms. For example, there are thousands of firms participating in the U.S. Natural Gas market; indeed, the largest producer (Exxon-Mobil) only accounts for roughly 0.6% of the U.S. market. Similarly, during much of the heyday of the uranium market in the U.S. there were over 100 actively extracting firms.

An alternative explanation, which I believe is more empirically compelling, is that inventory holdings support the existence of equilibria in non-renewable resource markets. If firms hold inventories, then sales rates need not equal extraction rates, and so it does not matter whether firms are actively extracting or not. In this paper, I consider a model of non-renewable resource markets with empirically relevant features that induce firms to hold inventories. In addition to scale economies in extraction, I assume demand is subject to random shocks. Demand shocks induce fluctuations in market price, which in turn lead to variations in the firm's optimal extraction rate. So long as there is enough variation in production, relative to the overall downward trend that must occur for non-renewable resources, and if marginal cost is increasing in production, as would be true with U-shaped average costs, firms will wish to hold inventories to guard against future increases in costs [2,4]. This will be true no matter what current price is, and no matter what the current level of resources *in situ*. The presence of inventories allows market sales to adjust smoothly at any critical point in time where firms switch from actively extracting to not extracting, thereby supporting equilibrium.

As an empirical point, inventory holdings are important for many non-renewable resources. In Fig. 1, I illustrate annual inventory time series for nine natural resources.[3] These resources share some important features: substantial levels of private stockpiles were held over a long time period for each resource; these levels, which were often quite large in magnitude, commonly displayed substantial variation across time. While there are some differences in the temporal patterns between different resources, and while there have been marked reductions in inventory holdings for some resources, there is no disputing the broad empirical importance of natural resource inventories.

The paper commences with a discussion of the model in Section 2. I then analyze the optimal behavior from the firm's point of view in Section 3. The motivation to hold inventories is evaluated in Section 4. I discuss the implications for price paths that emerge from optimizing behavior, and consider the conditions for equilibrium to exist in Section 5. I discuss a variety of extensions in Section 6, and offer concluding remarks in Section 7.

2. A model with scale economies and stochastic prices

In this section, I develop a continuous time model of a non-renewable resource industry where extraction costs are non-convex, and prices follow a random process. To this end, I incorporate aspects of the models previously studied by

[2] Both ELH and Lozada argue that chattering controls can be ruled out by assuming extraction paths are piecewise continuous. An anonymous referee points out that one could still approximate a chattering control with a sequence of piecewise continuous functions, where the firm switches between producing at a positive rate (for example, at minimum average cost) and not producing at ever-shorter intervals. Accordingly, it would seem something more fundamental is required to preclude chattering controls. A more promising restriction, which I believe has empirical merit, is the presence of significant adjustment costs associated with shutting down or restarting extraction [14, p. 157].

[3] The data for these figures was taken from the United States Geologic Survey website, which can be accessed at http://minerals.usgs.gov/minerals/pubs/commodity/. Here, one can find data for a wide range of minerals. The resources included in Fig. 1 have data over a reasonably long time frame, and are representative of the broader sample. The resources illustrated are: Beryllium, Cobalt and Helium (first row); Lead, Molybdenum and Quartz Crystals (second row); Soda Ash, Sulfur and Zinc (bottom row). Other authors have found similar patterns to those illustrated here: Stockpiles of copper and heating oil are commonly 150–300% of annual consumption [27,28]. Similarly, inventory holdings are important in markets for coal, gold, silver, uranium, and petroleum products [29].