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Abstract

Despite the central role of the Hotelling model within the theory of nonrenewable resources, tests of the model are rarely found. If existent, these tests tend to ignore two key features, namely market power and exploration. We therefore suggest an extension of the basic Hotelling framework to incorporate exploration activity and market power and propose an implicit price behavior test of the model to indicate whether firms undergo inter-temporal optimization. When applied to a newly constructed data set for the uranium mining industry, the null hypothesis of the firm optimizing inter-temporally is rejected in all settings. However, parameter estimates of the model still yield valuable information on cost structure, resource scarcity and market power. Our results suggest that the shadow price of the resource in situ is comparably small and may be overshadowed by market power, which may serve as an explanation for the firm failing to optimize inter-temporally.

Keywords: Hotelling rule, Resource Economics, Resource Scarcity, Dynamic Optimization, Exploration, Market Power, Hausman Test

JEL classification: D92, L13, L72, Q31

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1. Introduction

There is hardly a field in economics that has been influenced by one single publication as much as the field of resource economics. Harold Hotelling published his work on the economics of exhaustible resources in 1931 (Hotelling, 1931). The paper gained attention in the 1970s due to the oil embargo and the subsequent energy crisis as well as the debate initiated by Meadows et al. (1972). Even today, the assumption of inter-temporal optimization within the nonrenewable resource industry, as introduced by Hotelling, is the foundation for many policy recommendations as seen in Hans-Werner Sinn's green paradox (Sinn, 2008).

Even though Hotelling's theory maintained academic attention for over 80 years, empirical applications and tests of the theory are rarely found mainly due to the vast number of influencing factors within the model paired with the unavailability of appropriate data sets. However, in order to derive policy recommendations, such as the ones implied by the green paradox, understanding the significance of the theory is crucial. Thus, the question as to whether the scarcity of a nonrenewable resource influences the actual decision-making process of a mining industry is the focus of this analysis.

This process depends on the value of the resource in situ (which can be represented by the shadow price, the scarcity rent or the user cost) and whether it is large enough to be incorporated into the firm's choice of variables. The relative size of the shadow price of the resource in situ compared to the full cost of production crucially depends on different characteristics of the extraction and processing of the resource as well as the market in which the firm is operating. Two factors that directly influence the shadow price and its relative size have thus far been neglected in the majority of empirical works on the Hotelling rule: First, the resource shadow price depends not only on the extraction decisions but also on decisions made in order to increase the resource stock by exploratory activities. Second, the significance of the shadow price depends on whether other rents, e.g., market power mark-ups, take up larger shares and, thus, possibly dominate the decision-making process.

In our analysis we therefore incorporate the concepts of exploration and market power into the Hotelling model. Applying empirical methods and using data from a newly constructed data set for the uranium mining industry, we study the consistency of the behavior of the shadow price with the Hotelling model and perform an implicit price behavior test for a major firm in the industry. We estimate two models: one accounting only for the static optimality implied by the Hotelling model and another accounting additionally for dynamic optimality. Under the null hypotheses of the firm extracting the resource according to the inter-temporal optimum, estimation of both models should lead to equivalent results. Our tests show that the null hypothesis is rejected in all of the settings analyzed, thus suggesting that the firm is failing to extract at the dynamic optimum. Despite this rejection, parameter estimates of the model still allow us to derive information on costs, resource scarcity and market power mark-ups. These estimates suggest that the shadow price of the resource in situ is comparably small and may be overshadowed by market power, which may explain why the firm fails to optimize inter-temporally.

The remainder of this article is structured as follows: Section 2 presents existing literature on the topic. Section 3 describes our extension of the Hotelling model, while Section 4 introduces the applied econometric framework. Section 5 introduces the applied data set. Test results and parameter estimates are discussed in Section 6. Section 7 concludes.

2. Literature Review

Hotelling (1931) was the first to introduce and solve the inter-temporal optimization problem in nonrenewable resource economics. As a consequence, the concept of the shadow price (user costs) of the resource in situ was also established. Academic and public interest was low until the end of the second half of the last century when the publication of Meadows et al. (1972) and Solow's lecture on Hotelling's model (Solow, 1974) boosted interest in the theory of nonrenewable resource extraction. Subsequent additions to the literature are extensively surveyed by Krautkraemer (1998). Today, Hotelling's work is considered to be the foundation of resource economics and plays a significant role in the discussion on climate change and, e.g., in the discussion on the green-paradox (Sinn, 2008).

As academic interest rose, first tests of the theory began to be conducted. Different analyses have since been done, which Chermak and Patrick (2002) classified into two main groups: price path and price behavior tests. Price path tests examine whether the price of a nonrenewable resource changes according to Hotelling's "r-percent rule" (i.e., whether the price increases at the rate of interest). None of the price path analyses done by Barnett and Morse (2013), Smith (1979) and Slade (1982) could find evidence for the theory in actual data. However, these tests come with strong assumptions resulting from simplifications in Hotelling's model: First, technology is assumed to be constant over time and second, the relation of extraction costs to the resource base and marginal costs is not considered.

Price behavior tests incorporate the price path into the decision-making process of the extracting firm. Explicit price behavior tests assume a process that consists of extraction and direct selling of the nonrenewable resource. This implies that the extracted resource is not processed and therefore marginal costs are simply given by the extraction costs. The results of these analyses are ambiguous: While Farrow (1985) and Young (1992) reject the theory, Stollery (1983) and Slade and Thille (1997) obtain positive results whereas

Miller and Upton (1985) present mixed results. As Chermak and Patrick (2002) point out, even though the test approach is similar across analyses, data handling and underlying assumptions vary strongly.

For most nonrenewable resources, processing of the resource is a necessary step (e.g., extraction of the mineral of interest from the ore) before the good can be sold. As the majority of mining firms can, in general, be considered vertically integrated (i.e., offering both mining and processing of the resource), explicit price behavior tests are not applicable to most nonrenewable industries. Implicit price behavior tests, on the other hand, take vertical integration into account. The results of previous analyses considering implicit price behavior are again mixed. While Halvorsen and Smith (1991) reject the theory, Chermak and Patrick (2001)[1] obtain positive results. Caputo (2011) develops a nearly complete set of the testable implications of the Hotelling model; however, he finds that data inadequacies prevent testing all the implications of the theory. Compared to Caputo's analysis, the test in this paper could be considered to be only a partial test, as we closely follow the approach of Halvorsen and Smith (1991).

Table 1[2] gives an overview of the tests conducted thus far and their main characteristics. It becomes obvious that the tests do not only vary in their testing approach but also in the data time resolution and level. Furthermore, almost all articles assume perfect competition in the input and output markets. Exploration activities as a means of increasing the resource base are generally not considered.

Assumptions of perfect competition or monopoly market structure for nonrenewable resource markets have been the norm ever since Hotelling (1931). The idea that this may not be an appropriate assumption for the mining industry was first empirically shown by Ellis and Halvorsen (2002). They extend the general Hotelling framework with respect to a one-shot Nash-Cournot oligopoly and find that prices substantially exceed marginal costs in an application to the international nickel industry. However, these mark-ups can be attributed to a large extend to market power rather than the resource scarcity rent.

[1] Using data from Chermak and Patrick (2001) and the test approach of Halvorsen and Smith (1991), Chermak and Patrick (2002) do not reject the theory.

[2] The table is a slightly extended version of the table found in Chermak and Patrick (2002).

Article	Test type	Time	Level	Product	Market	Exploration	Result
Barnett and Morse (2013)	Price path	Annual	Cross-industry	Various	Price taking	Not considered	Reject
Smith (1979)	Price path	Annual	Cross-industry	Various	Price taking	Not considered	Reject
Slade (1982)	Price path	Annual	Cross-industry	Various	Price taking	Not considered	Reject
Farrow (1985)	Explicit price behavior	Monthly	Single mine	Metals	Price taking	Not considered	Reject
Miller and Upton (1985)	Explicit price behavior	Monthly	Firm	Oil/gas	Price taking	Not considered	Mixed
Stollery (1983)	Explicit price behavior	Annual	Firm	Nickel	Price leader	Not considered	Do not reject
Young (1992)	Explicit price behavior	Annual	Individual mine	Copper	Price taking	Not considered	Reject
Slade and Thille (1997)	Explicit price behavior	Annual	Individual mine	Copper	Price taking	Not considered	Do not reject
Halvorsen and Smith (1991)	Impl. price behavior model, expl. price behavior test	Annual	Cross-industry	Metals	Price taking	Not considered	Reject
Chermak and Patrick (2001)	Implicit price behavior	Monthly	Individual well	Natural gas	Price taking	Not considered	Do not reject
Caputo (2011)	Implicit price behavior	Annual	Individual mine	Copper	Price taking	Not considered	-

Table 1: Overview of different tests of the theory of nonrenewable resources

The impact of exploration activities and an extension of the resource base on the Hotelling framework was first investigated by Pindyck (1978). By allowing the firm to simultaneously decide on exploration activities (with certain outcomes) and resource extraction, they find that exploration activities and the resource price and production path are related: With an increase in reserves comes an increase in production. However, as the discovery of further reserves and, hence, the exploration activity declines, production also decreases. Subsequent research on exploration in the context of nonrenewable resources was surveyed by Cairns (1990) as well as Krautkraemer (1998). A noteworthy empirical application was made by Pesaran (1990). By investigating exploration and production decisions for oil at the United Kingdom continental shelf, they find a reasonable degree of support for the theoretical consideration of exploration in the Hotelling framework.

Our paper contributes to the existing stream of literature in at least two ways: First, our analysis combines the literature on testing of the Hotelling model, more precisely the implicit price behavior tests as presented in Halvorsen and Smith (1991), with the literature focusing on extensions of the Hotelling model, namely the extensions introduced by Ellis and Halvorsen (2002) and Pindyck (1978) regarding market power and exploration activity, respectively. Second, despite obtaining negative test results, our analysis allows us to provide suggestions for why firms may not optimize inter-temporally. More specifically, we find that market power mark-ups may cast a shadow on the scarcity rent and therefore incentivize short-term rather than long-term planning.

3. Theoretical Model

We follow the theoretical models of Pindyck (1978) and, in particular, Ellis and Halvorsen (2002). The inverse residual demand function of the firm of interest is assumed to be given by

$$P(t) = P\left(Q(t), T(t), Y(t), V(t)\right), \tag{1}$$

where P denotes the price of the firm's final product, Q the quantity of the firm's product, Y a set of exogenous demand shifters entering the demand system and V the firm-specific factor prices of the other firms including, e.g., location-dependent costs for labor and capital. The observable arguments of the residual demand curve are threefold: own quantity, structural demand variables and the other firm's cost variables. In specifying the residual demand curve, we closely follow the work of Baker and Bresnahan (1988).

The firm is assumed to maximize its profits U, which are defined as revenues minus full total costs FTC:

$$U(t) = P(t) \cdot Q(t) - FTC(t). \tag{2}$$

Abbreviation	Explanation
State variables	
χ	Cumulative resource additions
S	Amount of proven resources
Control variables	
E	Extraction rate
Q	Rate of final output
B	Exploration expenses
Parameters	
T	State of technology
P	Market price of final output
W	Market price of reproducible inputs (labor, capital)
X	Amount of reproducible inputs (labor, capital)
r	Real interest rate
λ_1	Shadow price of reserves (i.e., resource in situ)
λ_2	Shadow price of cumulative discoveries
Functions	
f	Exploration function
R	Revenue function
U	Utility function
V	Firm-specific factor prices of competing firms
Y	Exogenous global demand shifters
CR	Restricted cost function
FTC	Full total costs
FMC	Full marginal costs
Subscripts	
K	Capital
L	Labor
CAP	Global thermal capacity of nuclear power plants
MFM	Recycled warheads ("Megatons for Megawatts")
INV	Changes in global uranium inventories
LAU, LKZ	Labor Australia, Kazakstan
KAU, KKZ	Capital Australia, Kazakstan
SAU, SKZ	Proven reserves Australia, Kazakstan

Table 2: Notation

The necessary first order condition gives

$$FMC(t) = \frac{\partial FTC(t)}{\partial Q(t)} = P(t) + \frac{\partial P(t)}{\partial Q(t)} \cdot Q(t), \tag{3}$$

where FMC denotes the firm's full marginal costs, obtained by taking the derivative of the firm's full total cost with respect to its own quantity.

In order to derive the firm's full marginal costs, we have to analyze the firm's decision-making process in more detail. The firm operates a two-stage production process: In the first stage of production, a nonrenewable resource is extracted and fed into the second stage of production, where it is processed into a final output. We thus assume a vertically integrated firm, which holds true for most companies in resource industries. The production function of the firm is given by

$$Q(t) = Q(E(t), X(t), S(t), T(t)), \tag{4}$$

where E is the extraction rate of the nonrenewable resource, X is the amount of reproducible inputs (i.e., capital and labor), S the amount of proven resources and T the state of technology.

Dual to this cost function is the restricted cost function of reproducible inputs, CR, which is defined by

$$CR(t) = CR(Q(t), E(t), W(t), S(t), T(t)) \tag{5}$$

with W denoting the market price of the reproducible inputs (see Halvorsen and Smith, 1984). The firm's decision-making process is then given by the following (generalized) Hotelling model

$$\max_{E(\tau),Q(\tau),B(\tau)} \int_t^{\overline{T}} e^{-r(\tau-t)} \left[R(Q(\tau)) - CR(Q(\tau), E(\tau), W(\tau), S(\tau), T(\tau)) - B(\tau)\right] d\tau \tag{6}$$

$$\text{subject to:} \qquad \dot{\chi}(\tau) - E(\tau) = \dot{S}(\tau) \tag{7}$$

$$f(B(\tau), \chi(\tau)) = \dot{\chi}(\tau) \tag{8}$$

$$S(\tau), Q(\tau), B(\tau), \chi(\tau), E(\tau) \geq 0. \tag{9}$$

As shown in Equations (7) and (8), our model incorporates the exploration activities of the firm: Given a certain effort B and already discovered resources χ, new resources $\dot{\chi}$ are found by means of the exploration function $f(B, \chi)$. Consequently, the available stock is equal to discoveries minus extracted quantities. Pindyck (1978) introduced the concept of exploration into the Hotelling framework, arguing that producers "are not endowed with reserves but must develop them through the process of exploration" (Pindyck, 1978). Therefore, the producer's choice set is increased by the decision to invest in exploration activities. The approach in this article is to assume a set of characteristics for the exploration function f. Those include (i) increasing discoveries with increasing exploratory expenditures, (ii) diminishing marginal productivity and (iii) the discovery decline condition (see, e.g., Pesaran, 1990). Letting λ_1 and λ_2 denote the costate variables (or shadow prices) of Equations (7) and (8), we derive the Hamiltonian of the optimization problem as

$$H(t) = R(Q(t)) - CR(Q(t), E(t), W(t), S(t), T(t)) - B(t) - \lambda_1(t) \cdot (\dot{\chi}(t) - E(t)) - \lambda_2(t) \cdot f(B(t), \chi(t)). \tag{10}$$

In the following, time arguments are omitted for improved readability. The static optimality conditions, i.e., the first-order conditions of Equation (10) with respect to the control variables E, B and Q, are given by

$$0 = -\frac{\partial CR}{\partial E} + \lambda_1 \tag{11}$$

$$0 = -1 - (\lambda_1 + \lambda_2) \cdot \frac{\partial f}{\partial B} \tag{12}$$

$$0 = \frac{\partial R}{\partial Q} - \frac{\partial CR}{\partial Q}. \tag{13}$$

Following the maximum principle, Equations (11) to (13) state that the Hamiltonian has to be maximized by the control variables in every point in time t (Chiang, 2000). Rearranging Equations (11) and (12), the static optimality conditions result in the following equations for the shadow prices λ_1 and λ_2:

$$\lambda_1 = \frac{\partial CR}{\partial E} \tag{14}$$

$$\lambda_2 = -\left(\frac{\partial f}{\partial B}\right)^{-1} - \frac{\partial CR}{\partial E}. \tag{15}$$

The interpretations of Equations (13), (14) and (15) are rather straightforward. Equation (13) states that the firm chooses output quantity Q such that the marginal revenue equates the marginal changes in restricted costs CR. Equation (14) states that extraction is optimally chosen if marginal changes in restricted costs (due to changes in extraction E) correspond to the shadow price of the resource in situ λ_1. Finally, Equation (15) gives the relationship between the shadow price of exploration λ_2 and changes in the exploration function f with respect to exploration expenditures B as well as the shadow price of the resource in situ, which is equivalent to the marginal changes in restricted costs with respect to extraction E. This illustrates that, even though the restricted cost does not directly depend on the exploration activities, a connection exists via the amount of proven resources S and the values λ_1 and λ_2.

The dynamic optimality conditions of the generalized Hotelling model follow from the relation of the choice for the control variables and the state variables. The dynamic optimality conditions give the optimal path for the shadow prices (see, e.g., Chiang, 2000; Wälde, 2012)

$$\dot{\lambda_1} = \frac{\partial CR}{\partial S} + r \cdot \lambda_1 \tag{16}$$

$$\dot{\lambda_2} = (\lambda_1 + \lambda_2) \cdot \frac{\partial f}{\partial \chi} + r \cdot \lambda_2. \tag{17}$$

Inter-temporal changes in the shadow price of the resource in situ λ_1 equate changes in restricted costs CR with respect to the amount of proven resources S and the changes in interest rates r. Similar, inter-temporal changes in λ_2 result from variations in the interest rates but also from changes in the exploration function f with respect to cumulative resource additions χ[3], weighted by both shadow prices.

4. Econometric Model

The restricted cost function covers different variable types: E is an intermediate good, X_L and X_K are production inputs of capital and labor, respectively, Q is the output of the final good, and S is an environment variable. We approximate the true restricted cost function using an transcendental logarithmic (translog) functional form (see, e.g., Ray, 1982; Ellis and Halvorsen, 2002). The small time-span covered by our data (compared to innovation cycles in mining industries) allows us to exclude the state of the technology T from the cost function. Therefore, the interaction terms of the translog-representation of the restricted cost function are limited to the intermediate as well as the production input and output variables. We median-adjust our independent variables, allowing for first-order coefficient estimates to be interpreted as cost elasticities at the sample median (Last and Wetzel, 2010).

The restricted cost function is given by

$$\begin{aligned}\ln CR \quad = \quad & \alpha_0 + \alpha_Q \ln Q + \sum_j \alpha_j \ln W_j + \alpha_E \ln E + \alpha_S \ln S \\ & + \frac{1}{2} \sum_j \sum_k \gamma_{jk} \ln W_j \ln W_k + \frac{1}{2} \gamma_{QQ} (\ln Q)^2 + \frac{1}{2} \gamma_{EE} (\ln E)^2 \\ & + \sum_j \gamma_{jQ} \ln W_j \ln Q + \sum_j \gamma_{jE} \ln W_j \ln E + \gamma_{QE} \ln Q \ln E \end{aligned} \tag{18}$$

with $j \in \{K, L\}$ and L and K being subscripts for labor and capital. Symmetry and homogeneity of degree one in inputs are given by the following restrictions:

$$\begin{aligned} \gamma_{KL} &= \gamma_{LK} \\ \sum_j \alpha_j &= 1 \\ \sum_j \gamma_{jQ} &= \sum_j \gamma_{jE} = \sum_j \gamma_{jk} = \sum_j \gamma_{kj} = 0. \end{aligned} \tag{19}$$

We impose homogeneity in prices by dividing by one price and thus account for just one price in the estimation. Symmetry conditions are imposed directly into the model.

In order to increase estimation efficiency, we incorporate cost share equations into our system of equations. The cost share equations for production inputs follow directly from the logarithmic differentiation of the

[3] By the discovery decline condition: $\frac{\partial f}{\partial \chi} < 0$.

implicit cost function with respect to input prices (Ray, 1982):

$$M_K = \alpha_K + \sum_j \gamma_{Kj} \ln W_j + \gamma_{KQ} \ln Q + \gamma_{KE} \ln E \quad (20)$$

$$M_L = \alpha_L + \sum_j \gamma_{Lj} \ln W_j + \gamma_{LQ} \ln Q + \gamma_{LE} \ln E \quad (21)$$

with $M_K = W_K X_K / CR$ and $M_L = W_L X_L / CR$ equal to the shares of reproducible inputs in restricted cost.

Following Equation (3), the supply relation requires an expression for full marginal costs (FMC), which are given by the partial derivative of full total costs (FTC) with respect to output quantity Q.

In our model, FTC are represented by the sum of restricted costs, exploration expenditures, the shadow price of the resource in situ multiplied by the changes in resource stock and the shadow price of exploration multiplied by the discoveries from exploration:

$$FTC = CR + B + \lambda_1 (f - E) + \lambda_2 f. \quad (22)$$

From this, we derive the FMC as

$$FMC = \frac{\partial FTC}{\partial Q} = \frac{\partial CR}{\partial Q} + \frac{\partial CR}{\partial E}\frac{\partial E}{\partial Q} - \lambda_1 \frac{\partial E}{\partial Q} = \frac{\partial CR}{\partial Q} \quad (23)$$

given the firm sets E at its optimal level. Therefore, the marginal costs contain no direct expression of the unknown shadow prices λ_1 and λ_2 and therefore can be estimated without further transformations (see also Ellis and Halvorsen, 2002). An expression for the right-hand side is obtained inserting the specification for the restricted cost function, i.e., Equation (18):

$$\begin{aligned} FMC = \frac{\partial CR}{\partial Q} &= \frac{\partial \ln CR}{\partial \ln Q}\frac{CR}{Q} \\ &= (\alpha_Q + \gamma_{QQ} \ln Q + \sum_j \gamma_{jQ} \ln W_j + \gamma_{QE} \ln E)\frac{CR}{Q}. \end{aligned} \quad (24)$$

The relationship between the firm's own price and quantity and the other firms' supply responses is given by the inverse residual demand curve, which we specify following the methodology introduced in Baker and Bresnahan (1988). In other words, the inverse residual demand curve of the firm of interest covers the firm's price P and quantity Q as well as the other firms' factor prices V and global demand shifters Y. As shown in Baker and Bresnahan (1988), estimation results are not sensitive to the particular specification (i.e., log-log or linear-linear) of the inverse residual demand curve. For our application, it is convenient to apply a linear-log specification as it simplifies further calculations. Thus, the residual demand curve is specified as follows (Baker and Bresnahan, 1988):

$$P = \beta \ln Q + \sum_k \varrho_k \ln V_k + \sum_l \tau_l \ln Y_l.^4 \tag{25}$$

In order to allow for time-varying mark-ups, we apply a semi-parametric approach following Ellis and Halvorsen (2002) and Diewert (1978) and represent β as a polynomial function in time. In the subsequent estimation procedure, we estimate different functional specifications for the polynomial representation of β. Overall, we find robust estimation results and significant coefficients for $\beta(t)$. Results suggest that specifying the mark-up term as a biquadratic polynomial yields satisfactory results. Further insights on this procedure are displayed in the econometric appendix. It follows the inverse residual demand curve as

$$P = (\beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3 + \beta_4 T^4) \ln Q + \sum_k \varrho_k \ln V_k + \sum_l \tau_l \ln Y_l. \tag{26}$$

Having specified the FMC (Equation (24)) as well as the inverse residual demand curve (Equation (26)), we can transform and use these estimation equations to obtain the estimation equation for the supply relation, i.e., Equation (3). First, we take the first derivative of price with respect to firm quantity

$$\frac{\partial P}{\partial Q} = \frac{\partial P}{\partial \ln Q} \frac{\partial \ln Q}{\partial Q} = (\beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3 + \beta_4 T^4) \frac{1}{Q}. \tag{27}$$

The supply relation for estimation follows as

$$P = (\alpha_Q + \gamma_{QQ} \ln Q + \sum_j \gamma_{jQ} \ln W_j + \gamma_{QE} \ln E) \frac{CR}{Q} - (\beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3 + \beta_4 T^4). \tag{28}$$

We apply the implicit price behavior test by Halvorsen and Smith (1991). In doing so, we utilize the fact that estimation of the marginal cost function, cost share equation, inverse residual demand curve and supply relation (i.e., Equations (18), (21), (26) and (28), respectively) is consistent. The resulting estimates of this model represent the static optimization problem of the firm. However it should be noted that as static optimality in each point in time is a prerequisite for dynamic optimality, this result can also represent the dynamically optimal solution. Therefore, if the firm optimally extracted its resource, within the framework of the Hotelling model, the addition of the first dynamic optimality condition given by Equation (16) in the system of equations should result in the same consistent but more efficient estimates. Hence, under our null hypothesis, the estimates of one model without and another one with the dynamic optimality conditions give

[4] With $k \in \{LAU, LKZ, KAU, KKZ, SAU, SKZ\}$ and $l \in \{CAP, MFM, INV\}$. LAU and LKZ denote costs for labor, KAU and KKZ denote costs for capital and SAU and SKZ denote proven reserves in Australia and Kazakhstan, respectively. CAP denotes the global thermal capacity of nuclear power plants, MFM available quantities from military warhead recycling and INV changes in global uranium inventories.

the same estimates. Under the alternative hypothesis, both models give statistically different results. We compare the estimates of both models using a Hausman specification test. In order to estimate the model including the dynamic optimality conditions, we first need to derive the discrete time form of the dynamic optimality condition (16), which is given by

$$\lambda_1(t) = \frac{\partial CR}{\partial S}(t) + (1+r)\lambda_1(t-1). \tag{29}$$

With

$$\lambda_1 = \frac{\partial CR}{\partial E} = \frac{\partial \ln CR}{\partial \ln E}\frac{CR}{E} = \underbrace{(\alpha_E + \gamma_{EE}\ln E + \sum_j \gamma_{jE}\ln W_j + \gamma_{QE}\ln Q)}_{a^{\lambda_1}}\underbrace{\frac{CR}{E}}_{b^{\lambda_1}} = a^{\lambda_1}b^{\lambda_1} \tag{30}$$

and

$$\frac{\partial CR}{\partial S} = \frac{\partial \ln CR}{\partial \ln S}\frac{CR}{S} = \underbrace{\alpha_S}_{c^{\lambda_1}}\underbrace{\frac{CR}{S}}_{d^{\lambda_1}} = c^{\lambda_1}d^{\lambda_1}, \tag{31}$$

we obtain

$$a^{\lambda_1}(t)b^{\lambda_1}(t) = c^{\lambda_1}(t)d^{\lambda_1}(t) + (1+r)a^{\lambda_1}(t-1)b^{\lambda_1}(t-1). \tag{32}$$

Summarizing, we estimate two models. Estimating Model 1 (with dynamic optimality condition) and Model 2 (without dynamic optimality condition), under the null hypothesis, give equal estimates which implies that the firm optimally extracted its resource. If, however, the estimates are statistically different, the firm does not perfectly optimize inter-temporally. The two lists below summarize the equations used in each model.

Model 1 (without dynamic optimality condition):

1. The restricted cost function, Equation (18);
2. The cost share equation, Equation (21);
3. The inverse residual demand curve, Equation (26);
4. The supply relation, Equation (28).

Model 2 (with dynamic optimality condition):

1. The restricted cost function, Equation (18);
2. The cost share equation, Equation (21);
3. The inverse residual demand curve, Equation (26);
4. The supply relation, Equation (28);
5. The dynamic optimality condition, Equation (32).

Within our model, the market price of final output P, the quantity of final output Q, as well as the extracted resource quantities E, are endogenous and need to be treated in order to prevent biased estimates.

Having to deal with endogeneity and simultaneous equations, we utilize an iterative Three-Stage-Least-Squares approach (3SLS). Despite being linear in parameters, our system of equations will be nonlinear in endogenous variables due to transformations of the endogenous variables (e.g., interactions with other variables and squaring). Even though nonlinear transformations of endogenous variables are not necessarily a problem[5], we follow Wooldridge (2002) (Chapter 9.5) and use a set of squared and higher-order transformations of exogenous variables. In addition to exogenous variables already used in our system of equations, we introduce the following instrumental variables: $\ln Q^3$, $\ln Q^4$, $\ln S^3$, $\ln S^4$, $\ln P^3$, $\ln P^4$, T and T^2.

5. Data

We construct a dataset for the Canadian uranium mining firm Cameco Corporation. Uranium is particularly suitable for our methodology as long construction times for nuclear power plants contribute to long-term planning for resource extraction. Furthermore, the market for uranium mining shows considerable concentration on the supply side, with KazAtomProm, Cameco and Areva (as of 2013) covering almost 50% of global uranium production (World Nuclear Association, 2014). Hence, some execution of market power can be expected. Uranium mining firms are typically vertically integrated, i.e., they extract the resource as well as process it into a final product. The decision to choose Cameco was made for no particular reason other than it showed a better data availability compared to KazAtomProm and Areva. We use quarterly firm-level data for the years 2002-2012. While a detailed description of data sources and calculation steps is given in the data appendix, we introduce the main variables in the following (see also Table 2). Extraction rate E, rate of final output Q, exploration expenses B, market price of final output P, amount of proven reserves S and the amount of reproducible inputs for labor X_L and capital X_K (using the perpetual inventory method) are taken from Cameco (2012a) and Cameco (2012b). Prices for reproducible input labor W_L are based on Canadian average wages in the mining industry (Statistics Canada, 2013a), and prices for capital W_K are calculated from producer price indices, depreciation rates and real rate of interest $\tilde{r}$ (Statistics Canada, 2013b; Bank of Canada, 2014b).

The other firms' factor prices V used for the estimation of the inverse residual demand curve contain labor and capital costs as well as proven reserves. With the main competitors of Cameco active in Kazakhstan and Australia, we approximate the other firms' factor prices using values for these countries (e.g., Australia, 2013; ABS, 2014b; Agency of Kazakhstan of Statistics, 2014c). The global demand shifters Y cover the global thermal capacity of nuclear power plants (International Atomic Energy Agency, 2013), changes in

[5]With endogeneity corresponding to correlation of one variable with the error term, nonlinear transformations may eliminate the correlation.

global uranium inventories (Nuclear Energy Agency, 2011) and market quantities from military warhead recycling through, e.g., the "Megatons to Megawatts Program" (Centrus, 2014).

Specification of the exploration function f is done by extensively testing different functional forms using available firm-level data as well as extended data sets on Canadian exploration expenditures and discoveries (Nuclear Energy Agency, 2006). As no functional form proved consistent with (i) increasing discoveries with increasing exploratory expenditures, (ii) diminishing marginal productivity and (iii) the discovery decline condition, we have to assume that the multiplicative error term in the discovery function is large. Given the relatively low number of observations available, it makes it impossible to accurately estimate the exploration function.

Therefore, we use a functional form that deviates from the theoretic relationship specified in Equation (8). In the following, we use a simplified variant, given by $\dot{\chi} = f(B)$:

$$\dot{\chi}(t) = B(t)^{\underset{(11.1)}{0.4829}} \omega(t). \tag{33}$$

The error term associated with exploration activities is given by ω. The value in brackets below the exponent of the exploratory expenditures B represents the resulting t-value for this model.

This specification satisfies the conditions (i) and (ii) but can not account for the discovery-decline phenomenon (iii). The insignificance of the discovery-decline condition could correspond to numerous global discoveries made in recent years (similar results are obtained by Pesaran, 1990).

While quarterly data for exploration expenditures B are published by the firm (see also appendix), the amount of proven reserves S and hence resource additions $\dot{\chi}$ are only available on an annual basis. Therefore, we follow Little and Rubin (2002) and use the exploration function f to impute the resource additions $\dot{\chi}$. By using a multiple imputation approach, we estimate our model fifty times to account for different realizations of the error term in the exploration function.[6]

6. Empirical Results

Prior to comparing the estimates for Model 1 and Model 2, we first need to define the interest rate r in the dynamic optimality condition (32) of Model 2. We test the Hotelling model using different interest rates. Following Halvorsen and Smith (1991), we test constant discount rates (i.e., $r = 0.01$ to 0.25) as well as variable interest rates that are proportional to actual real (2012) Canadian interest rates $\tilde{r}$ (i.e., $r = \tilde{r} \cdot 0.25$

[6]We observe negative values for proven reserves in 76 out of 1650 imputed values (approximately 4.6%). These negative values give no solution in the logarithmic transformation and drop out of the sample.

to $\tilde{r} \cdot 4$). Test results indicate a rejection of the null hypothesis for both the constant discount rate (see Table 3) and the variable interest rate calculations (see Table 4) at the 1%-level, i.e., the firm's behavior does not satisfy the dynamic optimality condition.

Interest rate	χ^2 *test statistic*	*Interest rate*	χ^2 *test statistic*
0.01	5827.5***	0.14	23368.5***
0.02	5834.1***	0.15	23512.2***
0.03	5837.8***	0.16	23636.2***
0.04	5838.7***	0.17	23728.5***
0.05	5836.3***	0.18	23811.4***
0.06	5832.2***	0.19	23880.1***
0.07	5825.1***	0.2	23948.2***
0.08	21079.7***	0.21	23996.7***
0.09	21778.3***	0.22	24042.9***
0.1	22289***	0.23	24087.1***
0.11	22662.1***	0.24	24119.2***
0.12	22957.9***	0.25	24155.1***
0.13	23183.1***		

*** $p < 0.01$,** $p < 0.05$,* $p < 0.1$,$^{+}$ $p < 0.15$
The critical value (CV) for p=0.01 is at 37.5662

Table 3: Hausman test results for Model 1 and Model 1 at constant interest rates

Interest rate	χ^2 *test statistic*	*Interest rate*	χ^2 *test statistic*
$\tilde{r} \cdot 0.25$	5829.6***	$\tilde{r} \cdot 2.25$	22615.9***
$\tilde{r} \cdot 0.5$	5835.8***	$\tilde{r} \cdot 2.5$	22976.3***
$\tilde{r} \cdot 0.75$	5838.2***	$\tilde{r} \cdot 2.75$	23236.4***
$\tilde{r} \cdot 1$	5837***	$\tilde{r} \cdot 3$	23438.7***
$\tilde{r} \cdot 1.25$	5831.6***	$\tilde{r} \cdot 3.25$	23595.4***
$\tilde{r} \cdot 1.5$	5824***	$\tilde{r} \cdot 3.5$	23719.4***
$\tilde{r} \cdot 1.75$	21411.3***	$\tilde{r} \cdot 3.75$	23823.5***
$\tilde{r} \cdot 2$	22120.1***	$\tilde{r} \cdot 4$	23907.4***

*** $p < 0.01$,** $p < 0.05$,* $p < 0.1$,$^{+}$ $p < 0.15$
The critical value (CV) for p=0.01 is at 37.5662

Table 4: Hausman test results for Model 1 and Model 2 at proportional variations of the actual Canadian interest rate $\tilde{r}$

Even though the null hypothesis is rejected, estimation results of Model 1 provide information on cost factors, market power and the resource user costs. Table 5 gives the corresponding coefficients, standard errors and p-values.

Given the logarithmic form in Equation (19) as well as the convergence point set at the sample median, first-order coefficients for this equation represent the logarithmic first-order partial derivatives of the cost function and, thus, the cost elasticities at the sample median. Alternatively, the level-log specification of Equation (26) gives the absolute change in prices P under a percentage change in the independent variables (i.e., own quantity Q, the other firms factor prices V and global demand shifters Y).

Parameter	*Estimate*	*Std. Error*
α_0	20.736***	0.019
α_Q	1.33E-8***	3.65E-10
$\alpha_K = 1 - \alpha_L$	0.102***	1.49E-5
α_E	1.855***	0.045
α_S	-0.937***	0.057
$\gamma_{KK} = -\gamma_{LK} = \gamma_{LL} = -\gamma_{LK}$	-0.001***	7.29E-5
γ_{QQ}	1.22E-8***	9.71E-10
γ_{EE}	0.566***	0.09
$\gamma_{KQ} = -\gamma_{LQ}$	-7.69E-9***	4.52E-10
$\gamma_{KE} = -\gamma_{LE}$	0.002***	3.96E-5
γ_{QE}	-1.70E-8***	5.67E-10
β_0	-19.903***	0.509
β_1	0.024	0.027
β_2	0.088***	0.004
β_3	-0.001***	1.10E-4
β_4	-1.45E-4***	7.71E-6
τ_{MFM}	2.757	3.41
τ_{CAP}	92.04***	12.122
τ_{INV}	10.556***	0.06
ϱ_{LAU}	15.473***	0.835
ϱ_{LKZ}	13.2***	0.683
ϱ_{KAU}	23.736***	1.506
ϱ_{KKZ}	8.259***	0.501
ϱ_{SAU}	16.198***	0.985
ϱ_{SKZ}	-7.393***	0.841
Observations	2200	

$^{***}\ p < 0.01,^{**}\ p < 0.05,^{*}\ p < 0.1,^{+}\ p < 0.15$

Table 5: Estimation results for model without dynamic optimality condition (Model 1)

A majority of coefficients are statistically significant at the 1%-level. Furthermore, the first-order coefficients for the cost function (19) follow intuition: costs increase with higher costs for labor, capital, increased extraction and higher final output whereas costs decrease with larger reserves. With respect to the inverse residual demand function (26), the coefficients for the own quantity is of the expected sign whereas the other coefficients have no clear interpretation as they reflect direct and indirect effects due to adjustments made by competing firms (Baker and Bresnahan, 1988). The estimated coefficients are of plausible magnitude[7].

Apart from our main finding, that the firm fails to optimize inter-temporally, the estimation results for the cost function allow us to highlight firm/industry cost characteristics as a side note. First, processing of the good into the final output is much less cost intensive as is the extraction of the resource: Increasing extraction E by 1% corresponds to an average approximate increase in costs by 1.855%, whereas increasing

[7]Due to the logarithmic form of the restricted cost function, all α- and γ-coefficients represent percentage changes in the dependent variable with respect to changes in the corresponding independent variables. Therefore, plausible magnitudes are single-digit. Under the level-log specification of the inverse residual demand curve, all β-, τ- and ϱ-coefficients give level changes in the dependent variable, i.e., P, with respect to percentage changes in the independent variables. As the price levels vary between 31.75 and 57.38 (see Table 7), plausible coefficient magnitudes are in the lower half of the two-digit spectrum.

output Q by 1% hardly changes costs. Second, increasing the reserves, i.e., the resource base, by 1% through exploration results in an average approximate reduction in production costs of 0.937%.

The estimation results allow us to to directly calculate the market power mark-up in Equation (23) from the difference in the market price of final output P and $\partial CR/\partial Q$, which equals the FMC if the firm optimally chooses its control variables.

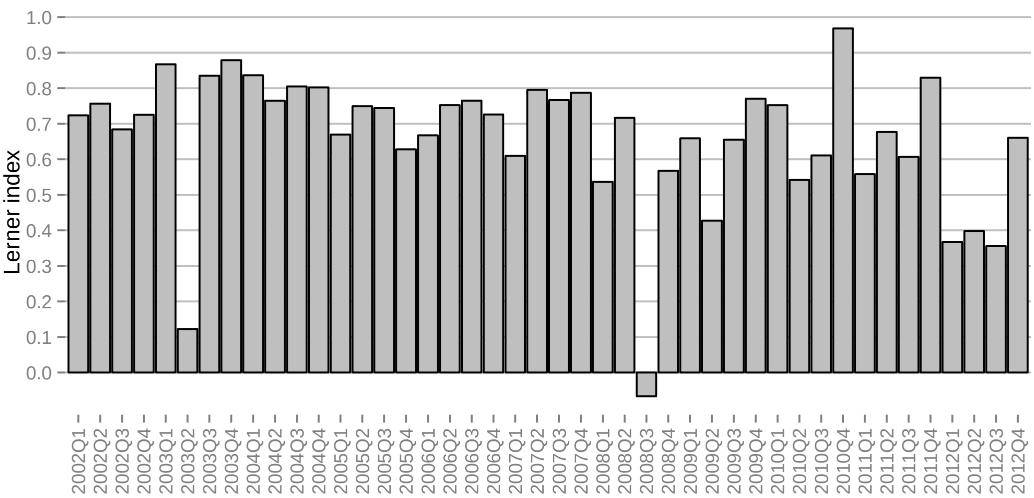

Figure 1: Lerner index

Figure 1 illustrates the Lerner index calculated from our model.[8] The graph clearly shows a substantial mark-up over marginal costs of approximately 0.7 for the first half of the last decade and a clearly decreasing trend towards 0.3 in the first half of 2012. Given that the mark-up corresponds to such a large share of the final output price, it becomes apparent that firms may optimize their output with respect to this mark-up rather than the optimal depletion of the resource.

We further derive an index of scarcity, as done in Halvorsen and Smith (1984), by computing an indexed version of λ_1 using Equation (30). The value for the first quarter of 2002 is set at 100. Figure 2 shows a drastic increase in resource user cost and, thus, an increasing scarcity of the resource. However, the large relative market power mark-up as well as the steep increase in user cost suggest a low absolute level of resource user costs.

[8]The Lerner index is given by $(P - \partial CR/\partial Q)/P$.

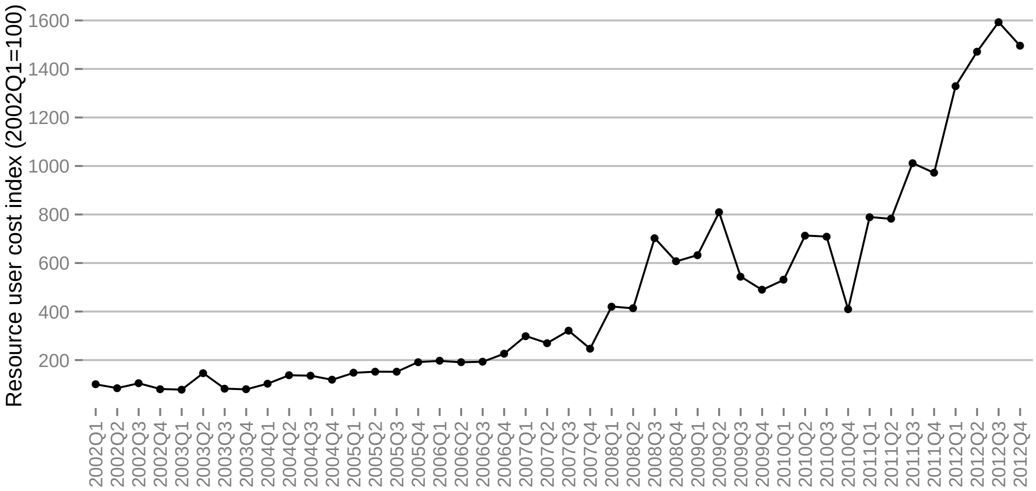

Figure 2: Resource user cost index

7. Discussion and Conclusions

In this paper, we present an extension of the Hotelling model incorporating two issues found to be omitted from previous research: market power and exploratory effort. Conducting an implicit price behavior test, we reject the null hypothesis of the firm optimizing inter-temporally. This complements prior research, which mostly failed to find evidence for the empirical validity of Hotelling's model.

Parameter estimates show that there exists a substantial mark-up over marginal costs that does not account for resource user costs. Thus, only a very small share of market prices could possibly represent resource user costs. Our results suggest that the hypothesis of Halvorsen (2008) holds, i.e., that user costs may be too small to be considered in a firm's decision-making process and that the 'mistake' firms are making by not optimizing inter-temporally may be small.

Furthermore, and as already stated by Halvorsen and Smith (1991), inadequacy of the theoretical model could be another likely reason for the theory to be rejected. Possible reasons for this inadequacy can be found in the assumptions made in the model. As we assume a uniform price for the good, we omit issues of transaction costs and imperfect information (also regarding foresight), which would arguably play a role in reality.

Similar to the test previously performed in other analyses, our results put the predictive power of the theory for nonrenewable resources into question. However, regardless of the (comparably) predictable uranium demand due to long nuclear reactor construction times, uncertainty prevails in the market, e.g., as a result of unknown international inventories. Therefore, relaxing the assumption regarding perfect foresight could be a promising next step in testing the theory of nonrenewable resources.

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Econometric Appendix

Wald test of perfect competition

As proposed by Ellis and Halvorsen (2002), we test our results regarding market power exertion against a null hypothesis of perfectly competitive price-taking behavior. Within our framework, perfect competition corresponds to $\beta_0 = \beta_1 = \beta_2 = \beta_3 = \beta_4 = 0$. We test the rejection of this null hypothesis using a Wald test. The resulting test statistic is found to be 2103.4. With a critical value 15.08, we reject the hypothesis of perfectly competitive behavior at the 1%-level.

Polynomial representation of $\beta(t)$

We estimate our Model 1 system of equations with five different polynomial representations of the time-varying mark-up. The specifications are as follows:

- Scalar representation: $\beta(t) = \beta_0$
- Linear representation: $\beta(t) = \beta_0 + \beta_1 T$
- Quadratic representation: $\beta(t) = \beta_0 + \beta_1 T + \beta_2 T^2$
- Cubic representation: $\beta(t) = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3$
- Biquadratic representation: $\beta(t) = \beta_0 + \beta_1 T + \beta_2 T^2 + \beta_3 T^3 + \beta_4 T^4$

The corresponding estimation results are given in Table 6. The results clearly show that almost all estimates (except for τ_{MFM} and ϱ_{LKZ}) are robust for different specifications. Therefore, we use the biquadratic specification as it reflects a higher order Taylor-approximation to the actual $\beta(t)$-function.

Parameter	*Scalar*	*Linear*	*Quadratic*	*Cubic*	*Biquadratic*
α_0	20.813***	20.816***	20.81***	20.801***	20.797***
α_Q	2.38E-8***	2.26E-8***	1.87E-8***	1.93E-8***	1.57E-8***
$\alpha_K = 1 - \alpha_L$	0.102***	0.102***	0.103***	0.102***	0.102***
α_E	1.564***	1.557***	1.436***	1.45***	1.576***
α_S	-1.511***	-1.496***	-1.489***	-1.509***	-1.397***
$\gamma_{KK} = -\gamma_{LK} = \gamma_{LL} = -\gamma_{LK}$	-0.003***	-0.003***	-0.002***	-0.002***	-0.002***
γ_{QQ}	2.72E-8***	2.47E-8***	2.47E-8***	2.37E-8***	1.64E-8***
γ_{EE}	0.201^{+}	0.207^{+}	0.412***	0.413***	0.493***
$\gamma_{KQ} = -\gamma_{LQ}$	3.83E-9***	4.15E-9***	-4.64E-9***	-3.06E-9***	-4.17E-9***
$\gamma_{KE} = -\gamma_{LE}$	0.002***	0.002***	0.002***	0.002***	0.002***
γ_{QE}	-3.06E-8***	-2.89E-8***	-2.25E-8***	-2.35E-8***	-1.95E-8***
β_0	-1.637***	-3.074***	-10.54***	-9.991***	-15.705***
β_1	-	-0.102***	0.039*	0.207***	0.113***
β_2	-	-	0.036***	0.034***	0.071***
β_3	-	-	-	-8.30E-4***	-1.00E-3***
β_4	-	-	-	-	-9.97E-5***
τ_{MFM}	5.878	6.622	13.968***	14.601***	7.255*
τ_{CAP}	49.492**	53.645**	40.312**	38.197**	47.112***
ϱ_{LAU}	16.148***	15.725***	12.594***	14.478***	13.756***
ϱ_{LKZ}	-1.614^{+}	-0.918	9.363***	9.27***	12.313***
ϱ_{KAU}	29.682***	28.147***	31.865***	28.697***	24.634***
ϱ_{KKZ}	3.064***	4.607***	8.514***	6.699***	7.255***
τ_{INV}	10.946***	10.887***	10.65***	10.783***	10.818***
ϱ_{SAU}	37.95***	37.29***	20.508***	21.741***	20.667***
ϱ_{SKZ}	-11.291***	-10.902***	-13.131***	-11.74***	-8.72***
Observations	2150	2150	2150	2150	2150

*** $p < 0.01$,** $p < 0.05$,* $p < 0.1$,$^{+}$ $p < 0.15$

Table 6: Estimation results for the model without dynamic optimality condition (Model 1) with different specifications for *beta*(t)

Data Appendix

Quantity of uranium extracted, E

Extraction volumes are taken from Cameco (2012b). Missing statements for the fourth quarter of the years 2008-2012 are calculated using first to third quarter values from Cameco (2012b) and annual values from Cameco (2012a).

Quantity of final output, Q

Sales volumes are taken from Cameco (2012b). Missing statements for the fourth quarter of the years 2008-2012 are calculated using first to third quarter values from Cameco (2012b) and annual values from Cameco (2012a).

Exploration expenditures, B

Exploration expenditures are given in Cameco (2012b). Quarterly expenditures are directly stated for the 4th quarter of the following years: 2008, 2009, 2010, 2011, 2012. Using information on annual exploration expenditures (Cameco, 2012a), quarterly values are calculated. In Cameco (2012b) and Cameco (2012a), monetary values are expressed in Canadian Dollar. Real (2012) values are calculated using the U.S. Consumer price index (CPI) (U.S. Department of Labor, 2013) (converted to quarterly values by weighting by the number of days per month) and Canadian to U.S. Dollar exchange rates. Exchange rates are expressed in Cameco (2012b). Missing data for the 4th quarter 2002 are substituted with data from Bank of Canada (2014a).

Additional exploration expenditure information for Canada used for estimating the exploration function, f, is taken from Nuclear Energy Agency (2006). Nominal values are converted to real (2012) values using Canadian Consumer Price Indices (OECD, 2013).

State of the technology, T

The state of the technology is expressed as a mean-adjusted linear trend.

Market price of final output, P

Data for the first three quarters of each year are taken from Cameco (2012b) using information on average realized prices. The market price for the final quarter of each year is calculated from annual data (Cameco, 2012b) weighted by sales volumes. Nominal values given in Canadian Dollars are converted to real (2012) U.S. Dollars using Canadian to U.S. Dollar exchange rates (Cameco, 2012b; Bank of Canada, 2014a) and Canadian Consumer Price Indices (OECD, 2013).

Market price of reproducible input labor, W_L

The market price of reproducible input labor in Canada is based on two data sources. Average weekly wage rates for Saskatchewan for forestry, fishing, mining, quarrying, oil and gas (North American Industry Classification System) (Statistics Canada, 2013a) are converted using U.S. Dollars using Canadian to U.S. Dollar exchange rates (Cameco, 2012b; Bank of Canada, 2014a) and U.S. Consumer Price Indices (OECD, 2013). Supplementary benefits are received by calculating the share of supplementary benefits in monthly wages from Statistics Canada (2012) and scaling the converted average weekly wage rates accordingly.

Quantity of labor, X_L

Annual data for direct employment in uranium mining operations in Canada is taken from Nuclear Energy Agency (2011). Data for Cameco are obtained by scaling total numbers using ownership shares for mining operations and assuming an equal distribution of changes among seasons.

Market price of reproducible input capital, W_K

Following Ellis and Halvorsen (2002), we calculate the price of capital as the product of the producer price index (PPI, for the mining industry if available), the sum of the depreciation rate (assumed to be at 10%) and the real rate of interest. We derive market prices for capital for Canada using the Machinery and Equipment Price Index (MEPI) for mines, quarries and oil wells (Statistics Canada, 2013b) as well as real interest rates calculated from data for selected Canadian 10-year bond yields (Bank of Canada, 2014b) and Canadian consumer price indeces (OECD, 2013).

Quantity of capital, X_K

Quantity of capital is derived via the perpetual inventory method. Year-end net value of property for the year 1996 as well as quarterly capital expenditures are taken from Cameco (2012a) and Cameco (2012b). Depreciation rates are assumed to be 10% and the producer price index is the Machinery and Equipment Price Index (MEPI) for mines, quarries and oil wells (Statistics Canada, 2013b). Exchange rates are from ABS (2014a) and X-RATES (2014).

Proven reserves, S

There are numerous classification schemes for uranium reserves and resources. We utilize definitions used by Nuclear Energy Agency (2011) and Cameco (2012a) and focus on proven reserves. Cameco (2012a) covers annual data for uranium reserves and resources. Quarterly values are imputed.

Recycling of military warheads, Y_{MFM}

Annual data for the "Megatons to Megawatts" quantities are given by Centrus (2014). We assume an equal distribution of quantities among quarters.

Global thermal capacity of nuclear power plants, Y_{CAP}

Global thermal capacity of nuclear power plants are calculated from plant characteristics, and commissioning and decommissioning dates taken from International Atomic Energy Agency (2013).

Global inventories, Y_{INV}

Inventory data is, generally speaking, not publicly available. Nuclear Energy Agency (2011) includes graphical information on global uranium production and demand from 1945 (i.e., approximately ten years prior to the commissioning of the first nuclear reactor) up to 2011. The difference between total production and demand is an approximate for global uranium inventories. Quarterly values are obtained from annual data from Nuclear Energy Agency (2011) using cubic splines.

Australian market prices for capital, V_{KAU}

Australian capital prices are obtained using PPI for the (coal) mining industry from ABS (2014d). Real (2012) rate of interest results from data for Commonwealth Government 10-year bonds (Reserve Bank of Australia, 2014) and inflation rates are calculated using ABS (2014c).

Kazakh market prices for capital, V_{KKZ}

Capital prices for Kazakhstan are based on the general PPI data from UNECE (2014). Using the Kazakh corporate bonds indix KASE_BY (KASE, 2014b) and CPI data from UNECE (2014), real (2012) interest rates are calculated.

Australian market prices for labor, V_{LAU}

Data for Australian mining operations is taken from ABS (2014b). In order to convert the data to real (2012) U.S. Dollar values, exchange rates from ABS (2014a) are used for January 2002 to March 2012. April 2012 to December 2012 are covered by X-RATES (2014). Both time series are weighted for quarterly values and adjusted using ABS (2014c).

Kazakh market prices for labor, V_{LKZ}

Kazakh mining industry monthly wage data for the years 2008 to 2012 is obtained from the Agency of Kazakhstan of Statistics (2014a). As sector-specific data is unavailable for years prior to 2008, we approximate mining wage data using changes in average wage statistics (Agency of Kazakhstan of Statistics, 2014c). Correlation between both series is shown via OLS estimation for overlapping observations (values in brackets represent t-values):

$$\text{avg. wage mining industry} = \underset{(-1.951)}{\text{-1.128E4}} + \underset{(27.924)}{1.993} \text{ avg. wage.}$$

Assuming strong correlation between GDP and wage growth (Warner et al., 2006, e.g.) and further decreasing unemployment with growth in GDP, we approximate mining sector wage data for Kazakhstan using Kazakh labor statistics for changes in unemployment (Agency of Kazakhstan of Statistics, 2014b). Again, correlation between both series is shown via OLS estimation for overlapping observations (values in brackets represent t-values):

$$\text{avg. wage mining industry} = \underset{(32.64)}{\text{4.901E5}} - \underset{(-25.91)}{671.36} \text{ unemployed population in thousands.}$$

Real (2012) values are obtained by conversion using KASE (2014a) and UNECE (2014).

Australian proven reserves, V_{SAU}

Australian annual data is taken from Australia (2013). Quarterly values are assumed to be identical to annual values.

Kazakh proven reserves, V_{SKZ}

Rempel et al. (2013) include annual data on Kazakh uranium reserves. Quarterly values are assumed to be identical to annual values.

Canadian interest rate, $\tilde{r}$

See *Market price of reproducible input capital.*

Summary Statistics

Series	*Mean*	*Maximum*	*Minimum*	*Std. Dev.*	*Observations*
B	1.274332	4.070614	0.264269	1.029772	2124
$\ln CR$	20.84144	22.94147	19.08893	1.150019	2124
$\ln E$	0.022724	1.175044	-1.206911	0.460854	2124
$\ln P$	3.333787	4.049799	2.470928	0.520859	2124
$\ln Q$	-0.054477	0.807969	-1.11201	0.278829	2124
$\ln S$	-0.042334	1.299977	-5.909206	0.665293	2124
$\ln W_K$	0.00044	0.662086	-0.359989	0.223815	2124
$\ln W_L$	0.00641	0.294694	-0.570092	0.203949	2124
M_K	0.102294	0.103997	0.099066	0.001333	2124
P	31.75191	57.38593	11.83343	14.49644	2124
$\bar{r}$	0.033211	0.048234	0.012374	0.009906	2124
T	0	21.5	-21.5	12.58251	2124
$\ln V_{KAU}$	-0.041982	0.134903	-0.29417	0.13467	2124
$\ln V_{KKZ}$	0.137492	0.61845	-0.446492	0.315771	2124
$\ln V_{LAU}$	0.061223	0.502522	-0.432324	0.258745	2124
$\ln V_{LKZ}$	-0.085882	0.288374	-0.742886	0.301522	2124
$\ln V_{SAU}$	-0.044462	0.217286	-0.318706	0.222694	2124
$\ln V_{SKZ}$	-0.049702	0.18477	-0.298063	0.124974	2124
$\ln Y_{CAP}$	-0.003819	0.012031	-0.031199	0.00964	2124
$\ln Y_{INV}$	2.98131	3.926857	2.093219	0.502895	2124
$\ln Y_{MFM}$	0.001745	0.054552	-0.029454	0.027657	2124

Table 7: Summary Statistics