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Issues in Extractive Resource Taxation: A Review of Research Methods and Models

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Issues in Extractive Resource Taxation: A Review of Research Methods and Models

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Abstract

This paper provides a conceptual overview of economists' attempts to learn about the effects of taxes on extractive resources. The emphasis is on research methods and techniques, with no attempt to provide a comprehensive tabulation of previous empirical results or policy conclusions regarding preferred tax instruments or systems. We argue, in fact, that the nature of such conclusions largely depends on the researcher's choice of modeling framework. Many alternative frameworks and approaches have been developed in the literature. Our goal is to describe the differences among them and to note their strengths and limitations.

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I. INTRODUCTION

This paper provides a conceptual overview of economists' attempts to learn about the effects of taxes on extractive resources. The emphasis is on research methods and techniques, with no attempt to provide a comprehensive tabulation of previous empirical results or policy conclusions regarding preferred tax instruments or systems. We argue, in fact, that the nature of such conclusions largely depends on the researcher's choice of modeling framework. Many alternative frameworks and approaches have been developed in the literature. Our goal is to describe the differences among them and to note their strengths and limitations.

The importance of resource taxation should be apparent. Mineral wealth plays a substantial role in many national economies. IMF (2012) identifies 22 countries where petroleum revenues comprise at least 10 percent of national GDP, a fraction that rises as high as 80 percent (Angola) or even 90 percent (Timor-Leste) in certain cases. Mining revenues typically constitute a smaller share of GDP but, due to surging commodity prices, this fraction is also large and growing. And extractive resources loom especially large as a source of government revenue. Boadway and Keen (2010) list 37 petroleum-rich nations where the fraction of government revenues drawn from oil and gas operations ranges between 10 percent and 97 percent, averaging 50 percent overall. A separate listing of 10 mineral-rich nations shows mining's share of total government revenue ranging between 1 percent and 44 percent, averaging 11 percent overall.

This variation in dependence upon resource revenues stems in part from differences in national resource endowments. The fact that 79 percent of Kuwaiti government revenue is derived from petroleum reflects the natural abundance of oil within the region. Even where resources are abundant, however, the government's share may be large or small depending on how provisions of the fiscal regime impact extractive industries. By "fiscal regime" we reference a broad variety of tax and contractual arrangements, including signature bonus payments, royalties, income tax, production-sharing, resource-rent taxes, and state participation, among others. Historically, individual governments have adopted various and unique combinations of these instruments, leading to a diverse and potentially confusing array of distinct fiscal regimes. No two countries tax extractive resources in quite the same way—which leaves researchers to ponder which type of regime is best.

The fiscal regime touches many aspects of an investor's plan of exploitation, including the scope of exploration and discovery, the timing and scale of initial development, the rate of production and decline, the timing and scale of enhanced recovery operations, the overall resource recovery factor, and the timing of final abandonment. The pervasive impacts of the fiscal system, on the investor as well as the government, magnify the importance of designing and implementing a sound fiscal regime. IMF (2010a, 2010b) reports that many resource-rich developing countries have failed to realize the full development potential of their natural resources and now seek to strengthen their ability to manage their resource sectors. The fact that, during 2006–12, IMF staff delivered 85 technical assistance missions to advise host governments on fiscal regimes for extractive resources, with an additional 33 missions already planned for 2013, indicates both the importance and complexity of this task.[1]

The performance of any system of resource taxation depends on (1) its ability to raise revenue; (2) potential distortions of private investment that impair resource value; and (3) the resulting allocation of risk between government and investor. To fairly assess these factors, one must recognize the many ways by which informed taxpayers adapt their activities to mitigate the tax.[2] A behavioral model is required, one that captures the potential for tax avoidance within the limits of the law and subject to the physical and economic constraints that define the extractive enterprise. Along these two dimensions (incorporating potential tax avoidance and accounting for the extractive nature of production) is where research methods and models tend to differ.

II. Literature Review

Any attempt to assess the impacts of extractive resource taxation must draw from two literatures: the economic theory of extractive industries and the theory of optimal taxation. This paper reviews the contributions of many preceding works that have attempted to conjoin these two subjects. A comprehensive review would necessitate a separate paper (or book) in its own right.[3] In lieu of that, we provide an overview of research that, although abbreviated, is sufficiently detailed to define the contribution of the various approaches. Although there is considerable overlap between the two fields, we have attempted to group together those studies that focus primarily on the economics of extraction, followed by a summary of applied research on tax distortions and optimal tax design as it relates to extractive enterprise.

A. The Literature on Optimal Investment and Extraction

The methods and models employed to study resource extraction from a known deposit cover a broad range. At one extreme are the highly detailed numerical reservoir simulation models developed by petroleum engineers. At the other extreme are applications of the generalized neoclassical theory of production set forth in graduate economics texts. Many alternative approaches lie between those two poles, and it is the intermediate methods that have tended to prove most useful and amenable for purposes of tax policy analysis. This section provides a brief overview of the various approaches.

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[1] See IMF (2012), Appendix 2. An outline of the IMF's technical assistance program is provided in IMF (2010a).

[2] As Poterba (2010) observes, understanding the taxpayer's behavioral response is what economic analysis adds to the accounting discussion of tax policy.

[3] Lund (2009) provides an excellent and comprehensive review of the literature on resource rent taxes. Peterson and Fisher (1977) and Cairns (1990) offer broad, if somewhat dated, reviews of the economics of exploration and extractive industries.

Reservoir simulation models

Peaceman (1977) provides a comprehensive technical overview and discussion of applications of reservoir simulation in the petroleum industry. By exploiting three-dimensional geological and geophysical modeling tools to capture the heterogeneous physical properties of a given reservoir, petroleum engineers are able to simulate fluid flows within a reservoir and forecast the production of oil, gas, and water expected to result from any particular drilling program. The dynamic properties of each simulation are governed by the rules of fluid dynamics (Darcy's Law) and the principle of material balance. When costs and values are assigned to the inputs and outputs, and after simulating the physical and financial consequences of alternative drilling programs, this approach comprises the most advanced and realistic tool with which to optimize the value of the resource. It also provides the most detailed way of examining the investor's behavioral response to taxes that would alter the pattern of net cash flows from any proposed plan of development.

Although the high level of spatial resolution (millions of grid blocks) required to attain precise projections can place prohibitive demands on computational resources, coarser simulation models (thousands of grid blocks) provide more practical forecasts of fluid flows that are quite accurate enough to be useful for reservoir management, as described by Durlofsky and others (1996).[4] Reliance on such models is standard practice within the petroleum industry, where large profits are earned by adapting development efforts to the unique physical characteristics of each reservoir. Due to their heavy information requirements and computational burdens, however, these models are seldom applied by economists for purposes of policy analysis.

One of the earliest and most successful attempts to incorporate engineering principles into an economic model of the extraction process is Uhler (1979), who formulated an integrated model of the exploration and extraction process. When applied in simplified form to a homogeneous reservoir, Uhler's approach leads directly to the exponential decline model—in which the rate of production from each well declines by a constant percentage each period—but his application also allows for pressure maintenance operations that would slow the decline rate and augment the volume of recoverable reserves. Identifying optimal extraction establishes the value of proved reserves in Uhler's model, which then provides the incentive that regulates the scope of exploration.

Another economic application of reservoir engineering principles is Jacoby and Smith (1985), where production from a non-associated gas reservoir is regulated by remaining resource volume, reservoir temperature, and pressure, in conjunction with the ideal gas law. Those physical variables are sufficient to determine the extent of decreasing returns to intensity of development (number of wells) and the resulting decline rate, which in conjunction with factor prices and the interest rate is sufficient to determine the optimal level of investment. Helmi-

[4] The size of each block in a highly refined simulation model can be as small as 1 cubic foot.

Oskoui and others (1992) take this approach to a higher level by taking account of reservoir heterogeneity. This added degree of realism is not without cost (25 equations in 25 unknowns). To keep the problem tractable, the number and location of wells is assumed to be predetermined. The benefits seem questionable: the authors' application to the Walton Canyon reservoir in Utah indicates a development program that would recover only 2 percent of the original oil in place, which seems low by an order of magnitude. The additional conclusion that severance tax, the depletion allowance, and income tax have no effect on the optimal program is equally surprising.

Rao's (2000) model is yet another attempt to explicitly relate well productivity to reservoir pressure and its determinants, but the focus is not on profit maximization per se, but on how exploration should be allocated across heterogeneous basins to minimize the aggregate cost of oil supply. There is little scope for optimization at the level of the individual reservoir in Rao's model since he applies predetermined production rates (i.e., reserve/production ratios) and fixed unit operating and investment costs to each reservoir within each basin.

Neoclassical approach to optimal extraction

The neoclassical theory of production starts from a more abstract conception of the deposit, which is characterized by a conventional production function that is subject only to certain constraints that are believed to apply to extractive industries (e.g., marginal costs that rise smoothly at an increasing rate with current production but decline with the volume of remaining reserves, non-negativity of physical flows, etc.). Subject to given factor prices, the optimal (profit maximizing) production path can then be characterized as the solution to a nonlinear programming problem.

Unlike reservoir simulation, neoclassical optimization methods produce an explicit forecast of production only in highly simplified special cases.[5] Rather, the method produces an implicit characterization of the optimal production path by artful interpretation of the first-order conditions, which serve as decision rules by which the manager of the deposit should act. Depending on details of the particular model, a few specific aspects of the optimal production path may emerge (e.g., installed capacity that is increasing with the expected price of output, and extraction that is non-increasing through time), but these prescriptive insights are typically not sufficient to permit detailed study of the comparative effects of alternative tax policies.

It should also be noted that the neoclassical approach is the logical extension of Gray's (1914) pioneering formulation of the problem as one of arithmetically maximizing the present value of the resource rent—a concept that was not well understood in the economics profession before his very influential paper appeared. Gray's formalization of the concept of mineral rent also set the stage for Hotelling's (1931) characterization of inter-temporal equilibrium in the market for an

[5] With simplifying assumptions regarding the impact of depletion on extraction costs and the rate of production, it should be possible to derive an explicit optimal extraction path. Whether the assumptions necessary to achieve that goal are realistic is another matter, and the literature has not really pursued that issue.

exhaustive resource. Although Hotelling's analysis is predicated on the assumption that each mine owner will strive to maximize the net present value of his resource, the familiar "Hotelling price path" is more a statement about the aggregate effects of those underlying optimization efforts than a recipe for optimal development of a particular resource deposit.

Numerous examples of the neoclassical approach to optimization are found in the mining literature, including Campbell (1980), Crabbe (1982), and Lewis (1985) who examine optimal capacity and extraction rates in a mine producing just one grade of ore. Stollery (1983) adds differentiated grades to the specification and examines the order of exploitation. Conrad and Hool (1984) also consider the multi-grade extraction problem, but to facilitate analysis of the influence of taxation on optimal investment they step down to a simplified version of the problem that includes only two time periods and only two grades. Fraser (1993 and 2002), and Fraser and Kingwell (1997) also take a neoclassical approach but under the further restriction that all extraction from the mine is assumed to occur in a single period, so the analysis is limited to the optimal scale of initial investment and does not address the optimal time path of exploitation.

Examples of the neoclassical approach applied to petroleum resources are also numerous. Cummings and Burt (1969) and Burt and Cummings (1970) are among the early researchers who were able to provide rules for exploiting an oil deposit and to characterize the optimal depletion path based on an analysis of the first-order conditions to a dynamic programming problem.[6] Kuller and Cummings (1974) take that analysis a step further by formulating and imposing constraints that are "consistent with the manner in which petroleum engineers think about production operations," including the causes and effects of declining reservoir pressure and the physical consequences of multiple producers drawing from a common pool.

Hyde and Markusen (1982) apply the neoclassical approach to integrated sequential investments in exploration and production, which leads to a two-stage optimization problem that is solved in the neoclassical tradition. But like the mining models of Fraser (1993 and 2002) and Fraser and Kingwell (1997), all production is assumed to occur in a single period. Also within the neoclassical tradition, Livernois and Uhler (1987) focus on the interdependence between a firm's exploration and development efforts, and show how profit maximization requires the firm to balance efforts on the intensive (extraction) and extensive (exploration) margins—with important implications for the evolution of finding and extraction costs, and for which their empirical tests based on some 166 Canadian oil pools show strong support. Cox and Wright's (1976) application of the neoclassical approach, with a CES production function that relates flow rate to

[6] The term "decision rules" is a bit strong. In the abstract context of the neoclassical model, decision rules are but verbal interpretations of the marginal conditions for optimization, such as "equating the immediate cost of capital investment with the discounted value of its rewards in future periods resulting from its direct effect on the profit function and indirect effect through the constraint set." (Cummings and Burt, 1969, p. 988). While such rules describe the guiding principles of efficient investment, it would be difficult to translate them into practical instructions that a mine operator would find useful.

the volume of remaining reserves and labor inputs, tests the impact of various fiscal instruments, including severance taxes, percentage depletion allowances, and regulatory pro-rationing. The empirical analysis, however, is aggregated at the regional level rather than at the level of the individual firm or field.

Contingent claims analysis

In contrast to the neoclassical approach, which is based on expected cash flows discounted to present value, Lund (1992) applies the contingent claims asset pricing technique to identify the optimal level of investment in a reservoir. This approach is particularly useful where uncertainty regarding future prices is thought to impact the value of current investment strategies. Since alternative tax instruments may influence the distribution of risk between investor and the host government, important insights may emerge by taking this perspective. However, with non-linear tax schedules, valuation of the contingent claims attached to an oil field requires rather extensive Monte Carlo simulation of each investment alternative, and the scale of the problem is hardly manageable without imposing fairly strong constraints on the underlying model of extraction. In Lund's application to North Sea fields, the optimization is conducted over alternative exploitation programs that are distinguished by a single parameter which merely scales up or down a predetermined inter-temporal pattern of production.

Blake and Roberts (2006) apply Lund's contingent claims approach to assess the potential distortion of development intensity wrought by a sample of five fiscal regimes. They also employ Lund's model of a hypothetical field, in which the time pattern of extraction is predetermined. Thus, as in Hyde and Markusen (1982), Lund (1992), Fraser (1993 and 2002), Fraser and Kingwell (1997), and Rao (2000), neither the optimal time-path of exploitation nor its sensitivity to alternative tax instruments are addressed.

Paddock, Siegel, and Smith (1988) apply option pricing techniques to value the exploration and development timing options embedded in typical petroleum leases. For any given field or prospect that is not too far "in the money," random price variation creates an incentive to delay exploration and development, and this applies even to highly profitable projects if substantial time remains before the lease expires. Option valuation incorporates the impact of price risk directly, using contingent claims analysis, and demonstrates that holding all else constant (including the expected value of the cash flow stream), increased price volatility increases the value of marginal investments and delays their initiation.[7] To the extent that a resource rent tax

[7] The incentive to delay stems directly from the option value of deferred development; i.e., postponing the irreversible investment to create production facilities until more information on future prices and costs is available to reinforce that decision. Holding *expected prices and costs constant*, the option value of a given project is increasing in the volatility (uncertainty) of those variables due to the greater likelihood of adverse price and cost movements that would undermine an immediate decision to develop—but which could be avoided by exercising the option to abort. The favorable impact of volatility is even greater on marginal projects than those that offer more lucrative profit margins. Thus, the value of marginal projects is especially enhanced by uncertainty in underlying factor prices.

(RRT) is neutral with respect to the scale of investment and operating decisions, it would not affect the underlying cash flow stream or project risk, and therefore would be neutral with respect to the timing of investment as well.[8] The timing impact of other fiscal regimes would depend on their impact on the underlying cash flow stream as well as how risks are shared. Pickles and Smith (1993) illustrate the option pricing method by an application to exploration prospects in the U.S. and the North Sea.

Although most economic models of extractive enterprise focus on the firm's investment decisions and operating behavior, the decision whether to hedge volatile output prices is also of some importance. Accordingly, Frestad (2010) examines the firm's optimal hedge ratio and how it is affected by the tax regime. His analysis shows that, if the firm's only incentive to hedge is to reduce expected corporate tax liabilities that arise from a convex corporate tax function, this incentive is not affected by the existence of an additional special tax that excludes derivative payoffs from the tax base (like Norway's special taxes on petroleum and hydropower), so the optimal hedge ratio is not affected. However, if the firm would also incur deadweight losses (e.g., costs of financial distress that arise when after-tax income is low), Frestad demonstrates that the presence of a special tax (which itself influences after-tax incomes and therefore the risk of a deadweight loss) may either increase or decrease the firm's optimal hedge ratio depending on the circumstances, but in most economically meaningful cases the optimal hedge ratio will fall. This particular line of research has yet to be tested empirically.

Decline curve models

The family of so-called "decline curve" models occupies a middle ground along the spectrum of reservoir modeling techniques. In contrast to the neoclassical approach, decline-rate models impose a lot of specific structure on the set of feasible inter-temporal production paths—structure that is inspired by knowledge of reservoir mechanics but simple enough in most applications to permit explicit identification of optimal investment and extraction paths. This characteristic facilitates detailed evaluation of all kinds of contingent and non-linear tax instruments that are difficult to incorporate in other modeling approaches. Unlike reservoir simulation models, decline-curve models treat the reservoir as a homogeneous deposit, which greatly reduces the information requirements and computational burden.

Decline-curve models have been used extensively for many years. Arps (1945) discusses the early development and application within the petroleum industry of exponential, hyperbolic, and harmonic decline curves to approximate and forecast reservoir behavior. Fetkovich (1980) demonstrates how these techniques, although simplified, are solidly grounded in the fundamental physical properties of fluid mechanics. Doublet and others (1994) show that decline-curve

[8] Hausman (2011) points out that distortions regarding the size and timing of ongoing investment might arise when assets are transferred between owners if the accounting rules fail to recognize the value of embedded options included in the transfer. But, as Lund (2011) argues, the resource rent tax per se does not distort the exercise of real options.

analysis yields excellent results without regard to the structure of the reservoir (size and shape) or the type of reservoir drive mechanism. Subsequently, the application of decline-curve models by petroleum engineers has become pervasive, to the point where the Society of Petroleum Evaluation Engineers (2002) has issued recommendations for standardized terminology.

Decline-curve models have also taken root in the economics literature. Adelman (1972, 1990, and 1995) applies the standard exponential decline model to show how optimal investment and extraction paths depend upon the amount of capital required to develop the reservoir, price levels, and the rate of interest. Smith and Paddock (1984) apply the exponential decline model to estimate regional differences in optimal extraction rates across a wide range of countries which include both onshore and offshore basins. One major drawback of the standard decline-rate models, however, is the implicit assumption that total production from the reservoir is rate insensitive; i.e., that ultimate recovery is independent of the intensity of reservoir development and speed of extraction. However, extensions of the model are possible to allow for variable recovery factors, as in Smith's (1995a) adaptation of the exponential decline model to evaluate the loss of reserves due to overproduction in Western Siberia.

Smith (2012) develops a further extension of the exponential decline model that distinguishes between primary and secondary phases of recovery, and which treats exploration and development in an integrated manner consistent with an investor's joint optimization of investments at both stages of the process. Although the model is a highly simplified abstraction of the actual exploration and development process, it incorporates the way that costs, prices, and taxes affect various margins of exploitation, including the scope of exploration in a given area, the timing and intensity of initial development of resulting discoveries, the timing and intensity of enhanced recovery methods, the overall resource recovery factor, and ultimate abandonment of the project.

B. The Literature on Petroleum/Mineral Tax Policy

Taxpayers adapt. Therefore, an overriding principle of intelligent tax design must be to account for behavioral reactions to the set of tax instruments under consideration. As Poterba (2010) observes: "In any analysis of tax policy and tax reform, it is essential to recognize that taxpayers respond to taxation." Although Poterba was primarily addressing the challenge in reforming the general income tax system in the United States, the principle applies with equal force to any special tax imposed on the natural resource sector. Even that most basic guidepost, the concept of tax neutrality, can hardly be applied unless one has, as Lund (2002) notes, a theory of how companies will behave. In the words of Triest (1998): "Reliable estimates of how tax incentives affect behavior are an essential input into the formation of tax policy."

The previous section reviewed economic models of optimal extraction, which provide the framework for anticipating behavioral reactions that might alter a firm's preferred plan for development once taxes are introduced. Those models are incorporated to various degrees in the studies of mineral and petroleum taxation reviewed in this section, with varied success. In every case, it should be noted that our ability to judge the performance of alternative tax instruments is necessarily limited by the nature of the underlying economic model that is chosen to drive the analysis.

Theoretical and conceptual foundations of tax policy

Many economic principles besides neutrality must be considered. The distribution of risk between government and industry, resilience to uncertain prices, and fair recovery of resource rents are perhaps foremost among many others. A comprehensive review of the issues that enter into tax policy is found in Boadway and Keen (2010). Regarding the distribution of risk, Leland (1978) provides a strong theoretical basis for structuring a tax system that exploits the differential ability of the two parties to tolerate uncertain returns, while being mindful of the firm's potential behavioral response. He shows, under a variety of conditions, that the optimal tax system must be neutral with respect to the firm's actions. Lloyd (1984) carries that analysis forward and argues that parameters of the optimal tax must be field-specific (or mine-specific in the case of minerals) since the nature and magnitude of risks may vary from one case to another. This result assumes that the government has the information on which to make such distinctions and the authority to discriminate among projects. Sebenius and Stan (1982) also consider the characteristics of efficient risk-spreading contracts, but they assume the underlying cash flow stream is predetermined and do not account for behavioral responses.

Tordo (2007) and Nakhle (2010) compare the main petroleum fiscal regimes and legal frameworks that apply in countries around the world. They identify certain features that are potentially desirable but also discuss some of the most controversial issues that arise in designing an effective regime. While no tax may achieve perfect neutrality, the argument in favor of the Resource Rent Tax (RRT), as originally put forth by Garnaut and Clunies Ross (1975), has convinced many authorities, but not all. Ergas, Harrison, and Pincus (2010), for example, discuss the informational burden that RRT places on government, and the potential for distortion if that burden cannot be met. This concern arises especially if the extractive enterprise subjected to RRT is closely integrated with other (non-taxed) downstream activities. Nellor's (1987) explanation of the preponderance of simple royalties over RRT is rather different. He argues that any system, like RRT, that gives early cash flows to the investor and postpones the government's return adds to sovereign risk and increases the chance that the investor's interest will ultimately be expropriated. On the other hand, empirical studies by Duncan (2006) and Manzano and Monaldi (2008) show that the risk of expropriation tends to increase when prices and profits rise. One might suppose that a simple royalty, or any other regressive system of taxation, would exacerbate that phenomenon due to the resulting countercyclical movement in government take, whereas an RRT system might help to alleviate it. Land (2010) provides an updated assessment of experience to date with the RRT.

Applied tax policy studies

It is difficult to group the applied tax policy studies, each of which is fairly unique, into broad categories. To gain a clear understanding of this rather large literature, however, some attempt at organization is warranted. The organizational principle used here is based on the scope of behavioral responses that enter into the analysis.

At one extreme are papers that adopt the “scenario” approach. These studies focus on “model fields” (or “model mines”), i.e., projects defined in terms of predetermined levels and timing of investment and production. Conclusions that emerge from the scenario approach therefore take minimal account of the taxpayer’s behavioral response.

The strictures of the scenario approach can be relaxed in various ways, as the foregoing review of extraction models would suggest. A number of models relax the time schedule or sequence of investments, but retain predetermined levels of investment and production. Other models optimize the level of investment and production, but assume that timing is predetermined. Relatively few models allow flexibility in both domains.

The Scenario Approach

In this approach, complete expenditure and extraction programs are described based on operations typical of a given geographical area, and the projected cash flow streams are then subjected to accounting analysis to determine, depending on the particular tax instruments and provisions in force, what will be the government take, distribution of risk, etc.

One advantage of the scenario approach is that calibration to local conditions is transparent. To a certain degree, judicious choice of model fields achieves external validity. Another advantage is to avoid the analytical burden and potential ambiguity of a more complicated (and perhaps less realistic) model of the field. The disadvantage is that the scenario approach accounts only in a very limited way for behavioral reactions to the tax instruments under review. In particular, consideration of tax neutrality is limited to the question of *whether* the field will be developed, not *how* or *when*. Thus, distortive taxes are those that raise the break-even field size or the break-even price level for commercial development. Distortion might also take the form of premature abandonment of the field. The division of rent between the investor and government, as well as the distribution of risk, can also be calculated, but any conclusions that might be reached are based on the implicit assumption that the taxpayer’s behavioral adjustments to the predetermined variables that define the model field (e.g., scale of investment, the rate of extraction, the timing of enhanced recovery methods, etc.) would not significantly alter the performance of the tax—or conversely, that the tax would not significantly alter the development of the field.

Despite its limited accounting for the taxpayer’s behavioral response, the scenario approach is frequently employed to compare the performance of real-world tax regimes. Much of this research has appeared in the form of business consulting reports. For example, Johnston (2003) and Van Meurs (1988 and 2012) each score a large set of international tax regimes according to performance measures calculated using the scenario approach. These analysts have made a successful business providing related software tools and training to business professionals around the globe, which signals broad acceptance of the scenario approach by industry and government. Academic researchers have also participated in the development of the scenario approach. Based primarily on scenario analysis, Kemp (1987, 1992, and 1994) has published extensively on the distortive impacts of various oil tax regimes in the North Sea, North America, Australia, China, Indonesia, and elsewhere. Smith (1995b and 1997) relies on the scenario approach in his studies of Russian and Latin American tax regimes. Tordo (2007) applies the scenario approach to examine the investment impacts of several variants of a progressive production sharing contract. Bacon and Kojima (2008) use the scenario approach to illustrate the tradeoff between revenue volatility and government income under regressive and progressive fiscal regimes. Daniel and others (2010) also take the scenario approach to compute indicators of fiscal performance for a group of 16 oil-producing countries. Hogan and Goldsworthy (2010) report on a similar analysis of 5 hypothetical mining projects subjected to 4 generic types of tax regime. Indeed, the scenario approach to tax analysis extends beyond the realm of petroleum and minerals: Amundsen and others (1992) employ it to study the comparative ability of tax regimes to capture economic rents from Norwegian hydropower stations.

One area where scenario analysis may seem well suited is the analysis of late-life royalty relief programs that are designed to avoid early abandonment of a producing field. Schiozer and Suslick (2003) study the shutdown decision using a scenario approach (where the time path of production is predetermined) to evaluate the impact of such programs. The question seems simple: with royalty relief, how long can the operator afford to let production run its course, and by how much would the additional flow increase total recovery? But a fiscal regime that includes royalty relief (or a regulatory environment that causes operators to anticipate royalty relief) might influence the operator's original plan of development, which determines intermediate recovery rates as well, with ambiguous consequences for total recovery. The scenario approach is not well equipped to resolve that ambiguity.

Timing of extraction

Zhang's (1997) analysis of North Sea oil fields is based on predetermined levels of investment and production, but not a predetermined starting date. His model includes random prices, which imparts positive value to the waiting option thus created. The value of the waiting option may also be interpreted as an additional (opportunity) cost of proceeding immediately. Given the firm's option to delay development, and in the context of the U.K. Petroleum Revenue Tax (PRT), Zhang demonstrates that a unique level of "uplift" is required to ensure neutrality with respect to timing.[9] He shows that the RRT is more robust than PRT with respect to timing as long as the threshold rate of return is high enough to include the value of the firm's option to delay development.

Panteghini (2005) formulates the firm's resource development problem as a sequential process and also tests the impact of an RRT-like fiscal regime on the timing of investments and production. Like Zhang (1997), he assumes predetermined levels of investment and production,

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[9] "Uplift" allows the investor additional tax deductions beyond the original amount of capital expenditure.

but provides for a richer behavioral response to the tax in the form of additional options to defer or restart the project. Specifically, the firm is assumed to hold an option to delay the initial investment, an option to expand production in the future, and an option to resume production that was earlier shut down. Like Zhang, Panteghini demonstrates that, if the threshold rate-of-return is high enough, the RRT will be neutral with respect to the timing of investment outlays. What might be surprising is his finding that *any* threshold above a certain minimum level, no matter how high, ensures neutrality. The intuition is quite simple: although a higher threshold would increase the value of the project to the firm if developed immediately, the value of the option to delay would also increase proportionately, leaving the criterion for exercising the option unchanged. Panteghini's results only address neutrality with respect to timing. Because the size of the investment is predetermined, his result does not prove that high threshold rates are neutral with respect to the *intensity* of development. And, if a high threshold rate might influence the size of the investment, then so might it influence the timing.

Intensity of development

Jacoby and Smith (1985) apply a highly simplified reservoir simulation model to analyze the impact of taxes on development of a hypothetical gas field subject to water drive located in the Gulf of Mexico. Although the time of initial investment is predetermined, with no option to delay development, the size of the initial investment, the number of wells, and the extraction rate are chosen by the operator to maximize expected profits. Royalties, windfall profits taxes, and profit-share taxes (as implemented in the U.S.) are all shown to have distortive effects that increase minimum economic field sizes, reduce the number of wells, and decrease the rate of extraction.

Boadway and others (1987) employ the neoclassical optimization approach to examine the impact of taxation on the activities of a hypothetical mining firm engaged in exploration, development, and production activities in Canada. Their analysis focuses on measurement of the marginal tax rates that apply to each stage of activity, rather than on obtaining an explicit solution to the firm's investment problem. Marginal tax rates are inferred from the difference between the marginal product of capital (net of depreciation) employed by a marginal mine and the cost of capital. This approach follows from the theory that the *marginal* mine will earn only the required rate of return so any net return beyond that must be captured by the taxing authority. By focusing on marginal tax rates, which turn out in many cases to be negative, the authors are able to infer the directional bias which the tax regime imparts to each stage of activity—but not the magnitude of those biases or the total effect on investment. The tax regime appears to stimulate exploration and development but to dampen extraction—which leaves the overall impact on production (which is the product of all three) somewhat in doubt.

Lund (1992) formulates a model to determine how a risk-averse firm would adjust its investment strategy, relative to a no-tax benchmark, under two versions of the Norwegian fiscal regime: the first being the pre-1987 regime which included royalty, corporate tax, and special petroleum tax with uplift provisions, the second representing the 1987 reforms which eliminated royalties and uplift and reduced the rate of special tax. Random price fluctuations, which are anticipated to occur over the life of the investment, influence the firm's after-tax net cash flow to a different extent depending on which tax regime is in force. Contingent claims analysis is applied to value these uncertain cash flow streams and quantify the difference in risk premiums between regimes. Although random price variation may create an incentive to delay development, this aspect of the problem is excluded from Lund's analysis; development is assumed to commence immediately. What the firm does control is the size of the development program, which may be scaled up or down subject to decreasing returns in terms of resource recovery. One similarity to the scenario approach is that the time pattern of extraction is predetermined independently of the firm's investment strategy. After the size of the firm's initial investment is fixed, the entire time-path of output is scaled accordingly. Given the nature of Lund's model, no analytic solution is available but the level of the firm's optimal initial investment is identified via Monte Carlo analysis and grid search. According to those results, both versions of the Norwegian regime are quite distortive—cutting the level of investment by half or more, which diminishes total (pre-tax) rents by some 25 percent.

Blake and Roberts (2006) apply Lund's (1992) model to five real-world tax regimes (Papua New Guinea, Alberta, Tanzania, and Trinidad, and the Sao Tome and Principe/Nigerian Joint Development Zone) and find in each case significant distortions to the intensity of development.

Hyde and Markusen (1982) formulate a two-stage model consisting of exploration followed, in the case of successful efforts, by development and production of the resource. Greater exploratory expenditure is assumed to raise the probability of success, and increased development expenditure is assumed to raise the ultimate recovery factor. The firm seeks to jointly optimize the intensity of exploration and development efforts, subject to further constraints. The first of these constraints is that the time-path of extraction is predetermined, as in Lund (1992). Although increased intensity of development will raise production overall, it will not change the time profile. Second, and quite importantly, all development expenditures must be made before the firm knows the size of its discovery. Indeed, the size of the discovery is not apparent until the last unit of resource has been extracted. Within this context, Hyde and Markusen consider the form of contract that will maximize the government's expected utility, subject to a fixed expected utility to be earned by the firm. They show that the optimal share of exploration and development risks borne by the firm are distinct quantities that will generally differ in magnitude if the firm and government differ in either risk aversion or risk assessment.

The treatment of exploration expenditures merits special concern due to the prevalence of "ring fence" provisions that may limit the firm's ability to set off the expense of unsuccessful exploratory efforts in one area against other projects or sources of income. Campbell and Lindner (1985) demonstrate that a RRT which fails to permit full recovery of exploration costs will discourage exploration, as one might expect. They also show that, even with full offset for exploration expense, if the firm is risk averse, then an increase in the RRT tax rate will result in less exploration of promising prospects and greater exploration of risky ones. The intuition for this result is that the greater allocation of risk to the government that is associated with a higher marginal tax rate has the same effect as a decrease in the firm's level of risk aversion. This highlights the fact that the neutrality of RRT depends not only on the nature of ring fence provisions, but on the assumption that the taxpayer is risk neutral. And, by extension of Ramsey's (1980 and 1981) insights regarding the impact of risk-of-ruin on exploration choices, one can see that RRT might, by reducing the risk-of-ruin, influence the composition of exploration portfolios even for risk-neutral firms (although Ramsey himself did not analyze the effect of taxes). The intuition for this is simply that even risk-neutral firms would not be guided by expected value alone if a project's downside risk could lead to bankruptcy that forecloses the opportunity to pursue additional projects in the future.

The neutrality of a RRT is also challenged by Fraser (1993), based on a model of the mine in which the operator chooses its investment in initial capacity to maximize expected profits. As in Hyde and Markusen (1982), the capacity decision must be made before the size of the deposit is known, which creates risk of excess capacity and low returns if the recoverable reserve turns out to be small. And if the reserve turns out to be large, there is no recourse to expand initial capacity to fully exploit the additional resource: any excess resource is simply foregone. Neither is there an option to delay development. In addition, extraction is assumed to occur all within one period, so the impact of the tax on the time path of extraction cannot be addressed. Subject to these constraints, Fraser finds that the existence of a neutral RRT is not assured. The reason (although this is not discussed in his paper), is that Fraser's version of the RRT does not permit the firm to offset losses against future income. As modeled, the regime ignores all losses but taxes gains, which obviously reduces the firm's incentive to invest. Fraser goes on to show that this distortion can be offset by increasing the threshold rate (which provides a greater the tax shield) until the full incentive to invest has been restored. However, the size of the tax shield required to exactly offset the risk of an unrecoverable loss depends on the size and probability of that loss—which in turn depend on the price/cost margin of the mine in question and the probability distribution of reserves. Fraser concludes that the neutral RRT threshold rate is, therefore, unique to each mine. He does not discuss the alternative approach in which neutrality can be achieved (assuming risk neutrality and no risk-or-ruin) with a uniform threshold rate if the government would permit the firm to deduct early losses from future income.[10]

Fraser and Kingwell (1997) apply Fraser's (1993) model to evaluate the relative tax revenue potential of RRT versus a simple royalty regime, and Fraser (2002) applies the model to compare the terms of U.K. and Australian profits taxes.[11]

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[10] As published, Fraser's (1993) analysis is misleading in another respect: his tax is not based on resource rent. Rather, the threshold for taxable income in his model is based on the absolute profit margin per unit of physical capacity—not the firm's realized rate of return (cf. his equations 2 and 3). The main qualitative results reported in the paper nonetheless stand even after this error is corrected. The easiest means of correction is to set the parameter "c"(the unit cost of building physical capacity) equal to unity throughout the paper, which then makes the profit margin per unit of physical capacity correspond to the firm's rate of return.

[11] The modeling error described in the previous footnote recurs in these two papers.

Hybrid models

Relatively few analysts or models provide the firm with options regarding both the timing of investments and the intensity of development. One notable effort of that type is Conrad and Hool (1984), whose model describes a mine with ore differentiated by grade. The operator may therefore optimize both the sequence in which grades are exploited and the intensity of that effort. Within that framework, Conrad and Hool demonstrate that the distortion caused by fixed-rate taxes (whether assessed on output, value, or profits) may be very different than the distortions created by variable rate taxes. Moreover, they conclude that progressivity destroys the neutrality of a profits tax with respect to grade selection, extraction rate, and overall recovery. It should be pointed out, however, that despite operator flexibility along two important margins, the overall level of capital investment is assumed to be predetermined. It is not clear how releasing that constraint would affect the authors' conclusions.

The dynamic programming approach to optimal extraction developed by Helmi-Oskoui and others (1992) also allows flexible timing and intensity of production, subject only to the physical laws that define the underlying reservoir simulation model, as described previously. In principle, this is the most sophisticated of all the models considered here, and might be expected to provide useful and fairly realistic projections of net cash flows from which the optimal development program can be derived. In fact, the approach may not live up to its potential. Within their case study, the model would have the operator postpone any development for 17 years, followed by 3 years of extraction, and then abandonment while fully 97 percent of the original oil-in-place remains untapped. This is unlike most development programs seen in the real world. Is it credible? That is difficult to say since the very complexity of the underlying model, and the method of its solution, acts as a black-box that prevents one from identifying the specific constraints, assumptions, and parameter values that may be driving the result.

Uhler's (1979) model is also a hybrid formulation that seeks to jointly optimize the rate of initial extraction and the timing and intensity of subsequent pressure maintenance operations. The implied value of developed reserves determines the level of exploration within a given geological play. Smith's (2012) analysis is similar in scope to Uhler, but driven by the exponential decline approach instead of more complex principles of reservoir simulation. This distinction makes for a simpler structure, one that can accommodate a more detailed model of the fiscal regime and simultaneously address many of the key tradeoffs that would influence the investor's decisions, including the scope of exploration, the timing and scale of initial development, the rate at which production declines during the primary phase of recovery, the timing and intensity of enhanced recovery operations, and the ultimate decision to abandon the field. Smith explores generic versions of six common fiscal regimes (royalties, corporate income taxes, fixed production-sharing, two versions of progressive production-sharing, and a resource rent tax), and finds that the investor's multiple adaptations across various margins of investment create some unexpected results. For example, despite the existence of a progressive tax structure, government take may not increase as prices rise, and higher royalty rates may prolong (not abridge) the period of exploitation.

III. Conclusion

Despite decades of study and experimentation, extractive resource tax policy remains in flux. Recent debates on the structure of resource taxation in Australia, Brazil, Russia, and the United States are indicative of the diversity of views that persist—even in the world's more advanced economies.[12] These policy debates are informed in part by a literature that includes many important contributions to our understanding of fiscal design, but which also encompasses a wide variety of techniques and modeling approaches. It is important to realize, therefore, how the various approaches differ, in terms of both assumptions and results.

Taxes impact various margins of resource development. To realistically model these effects, and their interactions, one ideally requires two things: (1) a versatile production model that encompasses the various stages of exploitation and respects the physical principles that govern (or at least constrain) extraction; and (2) a richly-detailed financial model of the fiscal regime in question. In practice, the difficulty comes in joining these two together. Most of the more physically robust models we have reviewed are confined to a single stage of activity and limited in their ability to accommodate complex fiscal structures of the sort encountered in the real world. As noted previously by Hyde and Markusen (1982), the investor's decision variables are often specified only in general terms, which increases the difficulty of extracting specific conclusions regarding fiscal design.

All of the models reviewed here attempt to account for the taxpayer's behavioral response—if only to a minimal extent. Most tend to focus on only one or another of the margins of investment; for example, the rate of extraction, or the timing of exploration, etc. Sometimes that approach gives useful results. But, the investor's response to any given tax instrument is the sum of adjustments on all margins, plus their interactions. It may be supposed, for example, that a high royalty rate would cause early abandonment of an oil field. Holding all else equal, that is undoubtedly true. But a high royalty may also limit the intensity of the investor's initial development program, which may in turn cause production to decline at a slower pace, thereby extending the life of the field. In addition, however, the high royalty may discourage application of enhanced recovery methods as the field matures, and an investor who anticipates this may elect to increase investment in initial capacity as a more profitable alternative to enhanced oil recovery (EOR). The total impact of the royalty on resource recovery, the investor's rate of return, and government revenues depends on the solution to this set of interrelated investment problems.

This is where the models we have reviewed differ most: in terms of their ability to recognize and integrate the taxpayer's adaptations across multiple margins of investment. Table 1 summarizes these differences. We close with the suggestion that, wherever possible, let tax policies for extractive resources be founded on the basis of models and methods that admit the broadest range of behavioral response. And let researchers continue their efforts to develop and refine models to that end.

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[12] See, for example, Box 3 of IMF (2012).

Table 1. Range of Permitted Behavioral Adaptations to Fiscal Stimuli: Model Comparisons

Study	Sector	Production Function	Timing of exploration	Scope of exploration	Timing of initial development	Scope of initial development	Production profile (decline rate)	Timing of enhanced recovery	Scope of enhanced recovery	Resource recovery factor	Minimum economic field size	Minimum economic price	Timing of abandonment
Bacon & Kojima (2008)	Oil & Gas	Scenario									x	x	x
Blake & Roberts (2006)	Oil & Gas	Scenario				x				x		x	
Boadway, et. al. (1987)	Mining	Neoclassical		x		x	x						
Campbell & Lindner (1985)	Mining, O&G	Scenario		x							x	x	
Conrad & Hool (1984)	Mining	Neoclassical				x	x			x			x
Daniel, et. al. (2010)	Oil & Gas	Scenario									x	x	x
Fraser & Kingwell (1997)	Mining	Scenario				x				x		x	
Fraser (1993, 2002)	Mining	Scenario				x				x		x	
Helmi-Oskoui, et. al. (1992)	Oil & Gas	Res Sim			x	x	x			x	x[1]	x	x
Hogan & Goldsworthy (2010)	Mining	Scenario									x	x	
Hyde & Markusen (1982)	Mining	Neoclassical		x		x				x			
Jacoby & Smith (1985)	Oil & Gas	Res Sim				x	x			x	x	x	x
Johnston (2003)	Oil & Gas	Scenario									x	x	x
Kemp (1987, 1992, 1994)	Oil & Gas	Scenario									x	x	x
Lund (1992)	Oil & Gas	Scenario				x				x		x	
Paddock, Siegel & Smith (1988)	Oil & Gas	Scenario	x		x						x	x	
Panteghini (2005)	Mining, O&G	Scenario	x		x			x					
Schiozer & Suslick (2003)	Oil & Gas	Decline Curve								x			x
Smith (1995b, 1997)	Oil & Gas	Scenario									x	x	x
Smith (2012)	Oil & Gas	Decline Curve		x	x	x	x	x	x	x	x	x	x
Tordo (2007)	Oil & Gas	Scenario									x	x	
Uhler (1979)	Oil & Gas	Res Sim		x		x	x	x	x	x	x	x	x
Van Meurs (1998, 2012)	Oil & Gas	Scenario									x	x	x
Zhang (1997)	Oil & Gas	Decline Curve			x							x	

[1] Could be implemented in terms of "minimum reservoir porosity," "minimum pressure," or "minimum permeability."

Notes: For each study, the table indicates which margins are under the investor's control. The meaning of "minimum economic field size" and "minimum economic price" is that the model determines thresholds at which the investor is assumed to condemn the project rather than invest.

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