Elastic Oil

A primer on the economics of exploration and production

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Abstract Predictions from the original geophysical approach to oil exploration and production suggest that oil production will develop according to a predetermined and inflexible bell-shaped trajectory, quite independent of variables relating to technological development, economics, and policy. Exploring potential sources of elasticity in oil reserves and production, this paper offers a modification to the geophysical approach. Based on economic theory and modern empirical research, the results suggest that both reserve-generation and production is indeed influenced by factors and forces of technology, economics, and government regulation.

Introduction

The sharp oil price increase over the last few years has increased the interest for security of energy supply in general, and for oil supply in particular. An important factor behind the oil price surge is strong economic growth in large parts of the world, but especially in newly industrialised economies like Brazil, Russia, India, and China. Another important factor relates to oil supply. So far, the response in oil supply to the latest price increase has been muted, partly due to financial pressures and enhanced capital discipline among international oil and gas companies (e.g., Osmundsen et al., 2007; Aune et al., 2007), but potentially also due to more fundamental factors relating to the non-renewable nature of fossil fuels. In this context, it is interesting to note that the most important petroleum provinces in the OECD area are faced with depletion (e.g., USA, Canada, United Kingdom, and Norway). International companies are therefore gradually shifting their attention and activities toward resource-rich countries in other parts of the world (e.g. Russia, Latin-America, Africa, and the Middle East).

Ultimately, global oil reserves are bounded by nature, with physical limits both to availability and production growth. One of the early proponents of the geophysical approach to oil exploration and production was Hubbert (1962), who argues that cumulative production is the key predictor of the rate of production. According to this view, the geological knowledge which has been gained in a region is best described by cumulative production. As the region matures, cumulative production will also capture the inescapable destiny of depletion. And since production is determined by the level of reserves, reserve depletion will also cause an ultimate dampening of both investment rates and production. In consequence, petroleum production will develop according to a logistic growth function, yielding bell-shaped trajectories for exploration activity, reserve additions, and production. The sort of production profiles generated by the geophysical approach to petroleum exploration and production is illustrated in the right-hand panel of Figure 1.[1]

Scale economies due to learning-by-doing (e.g., Quyen, 1991; Krautkraemer, 1998) will normally produce rapid growth in annual reserve additions from new discoveries in the early phase of development of a new oil province.[2] As the province matures, the average field size of new discoveries will tend down, and annual reserve additions will diminish. This is illustrated in the left-hand panel of Figure 1, whereby a bell-shaped curve for annual reserve additions gives rise to an s-shaped curve for cumulated volumes of discovered oil reserves.

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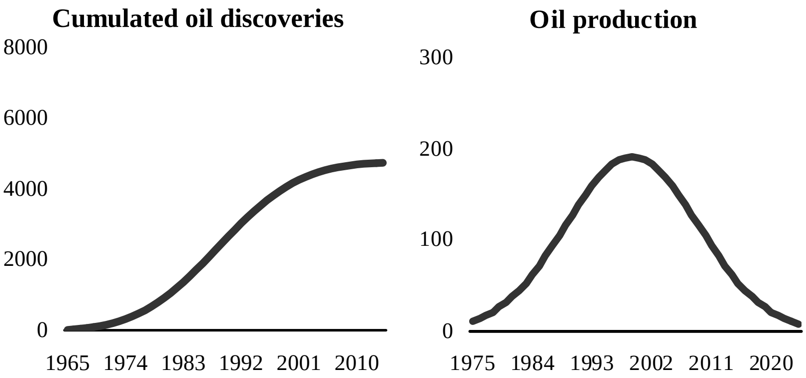
[1] The so-called Hubbert's peak was (quite successfully) applied to predict that US oil production would reach its maximum around 1970. The same concept has inspired the current debate of Peak Oil, with high-spirited discussions about when the world's oil production will peak.

[2] A popular analogy is found in the classic board game "Battleship". In the early phases of the game, with many ships on the board, expected rewards from bombing are high, with major learning effects involved whenever a new ship is hit. However, expected marginal gains, as well as learning effects, drop towards the end of the game, when the majority of ships have been sunk.

Figure 1. The geophysical perspective on oil exploration and production



Source: Stylised example based on author's calculations.

As opposed to scientists of geophysics and geology, economists like to think that oil production is governed by competitive companies' maximisation of expected profits. Consequently, economists put special emphasis on the influence of unit costs of reserve-generation and production, market developments, and policy regulations. This does not imply that economists entirely neglect the geophysical aspects of oil exploration and production. Rather, the physical perspective represented by Hubbert's peak is regularly taken as a point of departure, and augmented with models and variables based on economic theory.

An obvious conundrum for the geophysical approach to oil production relates to the actual development of global reserves and production rates over the last decades. The fact is that proved global oil reserves have increased by 75 per cent since the beginning of the 1980s. Annual rates of production have increased by nearly 40 per cent over the same period, and remaining global reserve life has gone from 30 to 40 years over the last 25 year period.[3] The static approach implied by the Hubbert curve fails in explaining this development (e.g., Lynch, 2002), and one important source of this shortfall relates to technological development (see also Watkins, 2006). Improved technologies have improved the reserve and revenue potential for reserve and revenue-generation, not only from exploration activities (e.g., Managi et al., 2005), but also from new techniques for increased oil recovery in producing fields (e.g., Watkins, 2002). At the same time, unit costs have been pushed down by technological progress. New solutions for exploration, development and production have implied a range of input-specific productivity gains, related to capital, labour, and energy. Economic models of oil exploration and production seek to embed these developments through appropriate mechanisms of technological progress, and through the incorporation of technology variables in empirical research.

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[3] According to BP's Statistical Review of World Energy 2007.

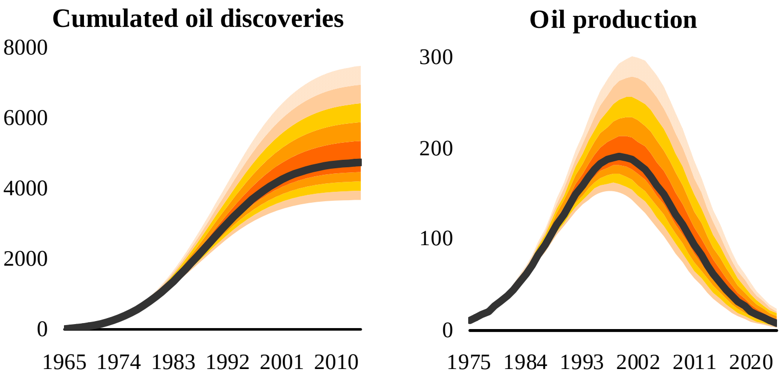
When geology meets the market there are also prices involved. The supply from profit maximising oil companies is determined by the equation between the oil price and marginal cost of production. Moreover, oil is an energy bearer that faces varying competition from other energy bearers, like coal, natural gas, and hydro-generated electricity. Finally, oil companies operate in variety of input markets, with direct exposure to varying costs of capital, labour, energy, materials, and other commodities. Consequently, oil investment and oil supply is likely to be influenced not only by the oil price, but also by a range other energy prices, and potentially also by shifts and shocks in input markets. To some degree, these mechanisms are also captured by economic models of oil supply.

Empirical studies of OPEC's role in the oil market have generally failed to establish firm evidence of stable cartel behaviour. However, recent studies do acknowledge that some sort of collusion is taking place. The current discussion is more about which model of imperfect competition the oil price formation adheres to, and to stability issues of OPEC's market power (e.g., Smith, 2005). Whatsoever, industry structure and macroeconomic management may have implications for incentives at the operational level. If the group of OPEC is seen as a dominant producer of an oil oligopoly, the strategic response to a lack of investment opportunities among their non-OPEC competitors does not necessarily imply an increase in OPEC investment (e.g., Aune et al., 2007). Moreover, oil investment and oil supply may not respond to high oil prices in countries dominated by national oil companies, as these companies may rather seek to stabilize government revenue than to maximize profits.

As the geophysical approach to oil production is focused entirely on the subsurface determinants of reserves and production, it also neglects the influence of government regulation. Governments play a role along the entire value chain of oil and gas companies. They control the access to exploration acreage, they approve any development project, they set the conditions for operations, and they design and impose systems of petroleum tax and government take. Moreover, governments also decide on how to manage petroleum resources, and not least how to deal with resource revenues. It follows that economic models of oil production also require a role for government regulation and policies.

All in all, the geophysical approach to oil exploration and production is improved if the modelling framework is extended to include processes and variables concerning of technology, markets, policy regulations, and market structure. Such an enhancement adds flexibility and elasticity to the geophysical approach. The result is a model that yields a better understanding of the interface between geology and economics, with improved predictions of both reserve-generation and production. This combined approach is illustrated in Figure 2, where an interval of elasticity is added for both reserve additions and for oil production. The shaded areas indicate possible outcomes for oil exploration and production, depending on local and global factors of technology, prices, market structure, and policy regulation.

Figure 2. The economic perspective on oil exploration and production



Source: Authors calculations.

The remainder of this chapter is organised as follows. Section 2 provides a brief review of previous economic research on oil exploration and production, with a special emphasis on empirical models. To shed light on the economic approach to reserve-generation, Section 3 gives a retrospect on exploration activities on the Norwegian Continental Shelf (NCS). A couple of empirical models are demonstrated in Section 4, again based on data from the NCS. Concluding remarks are offered in Section 5.

Previous research

As illustrated in Figure 2, the economic perspective on oil exploration and production usually introduces a rightward bias in the logistic growth framework of the geophysical approach, as demonstrated in an empirical assessment of the ultimate resource recovery by Pesaran and Samiei (1995). This implies that over time, resource additions tend to outpace the original geophysical estimates. In consequence, this also means that production rates will stay higher for longer than suggested by the simple Hubbert curve of Figure 1.

One important source of this bias relates to technological progress. Technological progress can be addressed from two perspectives. On the one hand, technological advances may exert a positive influence on the success rates in exploration and on the recovery rates of production. On the other hand, the dual approach is to view technological progress as a source of unit cost improvements. This would imply that technological advances induce an increase in yield per effort both in exploration and production. The accumulation of information and competence has the potential to improve the returns from exploration (e.g., Cleveland and Kaufmann, 1997; Managi et al., 2005), as well as net revenues of production (e.g., Farzin, 2001; Watkins, 2002). In exploration, significant technological advances relate to the collection and interpretation of geological information, improved operational drilling efficiency, as well as new technologies for real-time monitoring and measurement of the well's downhole conditions. According to Forbes and Zampelli (2000), technological progress increased the success rate in US offshore exploration by 8.3 per cent per year over the period 1986-1995. Similar advances in drilling technology are highly relevant also for production activities, as the investment in additional production wells become increasingly important when an oil field passes its peak, and embarks on the road towards depletion. Towards the tail-end phase of production, advanced reservoir management is combined with sophisticated drilling strategies to drain the reservoirs and to maximise resource recovery. Based on historical figures, Watkins (2002) finds that reserve appreciation over the lifetime of an average oil field amounts to some 20 per cent for the United Kingdom, and close to 50 per cent for Norway.

Another important deficiency in the original Hubbert model is its neglect of market mechanisms and price effects. Even though natural resources are bounded by nature, they are exploited by companies who adjust their behaviour according to market developments and prices (e.g., Lynch, 2002; Reynolds, 2002). Empirical exploration models for the US oil and gas industry are surveyed by Dahl and Duggan (1998), who conclude that acceptable models have been obtained for drilling efforts, with long-term oil price elasticities above one (see also Mohn and Osmundsen, 2008; Ringlund et al., 2008). However, there is reason to believe that drilling efficiency is also influenced by the oil price, as risk propensity in company investment is affected by its financial flexibility (Reiss, 1990; Iledare and Pulsipher, 1999). Based on time series data for the Norwegian Continental Shelf, Mohn (2008) finds that reserve additions are indeed enhanced by an increase in the oil price, due to responses both in effort and efficiency of exploration. His explanation is that oil companies accept higher exploration risk in response to an oil price increase, implying lower success rates and higher expected discovery size. Since the beginning of the 1990s, a series of studies have also augmented the simple Hubbert approach to oil production with economic variables, most notably the price of oil (e. g., Kaufmann, 1991; Cleveland and Kaufmann, 1991; Pesaran and Samiei, 1995; Moroney and Berg, 1999; Kaufmann and Cleveland, 2001). The research strategy of these studies has two stages. In the first stage, a reliable estimate is obtained for the Hubbert production curve. In the second stage, the deviation between observed production and the estimated Hubbert curve is modelled as a function of economic variables. All these studies show that economic variables are able to improve the quality of the original Hubbert model. However, the estimated oil price effects are modest, with elasticities of around 0.1 for the estimated production rates. The standard competitive model of supply has also been applied for empirical cross-country studies of oil supply (e. g., Watkins and Streifel, 1998; Ramcharran, 2002). In general, this class of models produces positive, but modest price elasticities for non-OPEC countries. On the other hand, the competitive model fails in providing a trustworthy description of OPEC supply.

The failure of competitive models in explaining OPEC supply behaviour is simply a reflection of the imperfect competition in the global oil market. In 1960, OPEC was founded to unite the interests of petroleum policies across member states. Since then, OPEC oil ministers have met regularly to discuss prices and production quotas. In 2006, OPEC countries accounted for 42 per cent of world oil production and 75 per cent of the world's proven oil reserves.[4] Empirical studies of OPEC's role in the oil market have generally failed to establish firm evidence of stable cartel behaviour. However, recent studies do acknowledge that some sort of collusion is taking place. The current discussion is more about which model of imperfect competition the oil price formation adheres to, and to stability issues of OPEC's market power (e.g., Fattouh, 2006).[5] A popular assumption for OPEC behaviour is the target revenue hypothesis, which implies that production is regulated inversely with price to uphold a revenue level which is adequate for exogenous investment and consumption needs (e.g., Alhajji and Huettner, 2000). The target revenue hypothesis imply that supply curves could be backward bending at high prices, which again could explain the muted investment response in OPEC countries to the current record oil price. However, as shown by Aune et al. (2007), net present value maximisation combined with the exploitation of market power is also consistent with OPEC supply and oil price formation over the last years.

Finally, governments also exert an influence on reserve-generation and production in the oil industry. For profit-maximising oil companies firms, profits are affected by tax systems and other forms of government take. Thus, incentives at the industry level may be affected by the regulatory system. In an econometric study of US exploration behaviour, Iledare (1995) incorporates the tax system in his proxy for the marginal value of reserves. In exploration activities, governments also play an important role as the ultimate holders of exploration acreage. Access to exploration acreage is determined by licensing systems and policies, which therefore have to be incorporated in models of exploration activity and reserve-growth. Based on data from the NCS, Mohn and Osmundsen (2008) illustrate how exploration drilling is stimulated by awards of new exploration acreage, and Mohn (2008) also find the size of average discoveries to be affected by licensing policies. Governments also play a role for the production phase of petroleum activity, with taxes and other systems of government take as the most notable transmission mechanism. As an example, a variable for pro-rationing of oil production in Texas prior to 1973 is included in Moroney and Berg's (1999) integrated model of oil supply. In general, tax systems have the potential of reducing investments and production growth (e.g., Boone 1998), distorting the optimal allocation of investments along the value chain,[6] and changing the distribution of capital for oil in-

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[4] According to BP's Statistical Review of World Energy 2007.

[5] See Smith (2005) for a critical overview of empirical studies of OPEC behaviour.

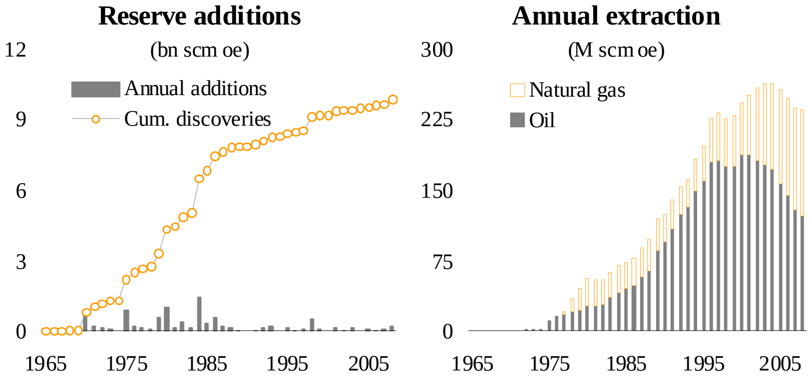
[6] Capital requirement along the value chain include investments in exploration activities, field development, efforts to increase oil recovery, processing and transport facilities, and potentially also marketing activities.

vestment between countries. See Glomsrød and Osmundsen (2005) for a recent overview of these issues.

NCS exploration and production

The Norwegian Continental Shelf (NCS) is a relatively young oil and gas province. Its petroleum potential was ignited among geologists by the discovery of the Groningen gas field in the Netherlands in 1959. The first discovery on the NCS was made in 1969, and the Ekofisk field was put on stream two years later.[7] A number of discoveries were made in subsequent years (cf. Figure 3), and these laid the foundations for the evolution of a new and important industry in Norway, and a supplying region for US and European oil and gas markets. Today, 53 NCS fields contribute to the total Norwegian oil and gas production at 236 M standard cubic metres (scm) oil equivalents (oe), with a natural gas share of some 40 per cent (2008). According to the Norwegian Petroleum Directorate (NPD), total oil production is now expected to continue its phase of gradual decline. On the other hand, gas production is seen to increase for another five years from today – to plateau levels of around 120 bn scm oe per year. For a thorough industry and policy overview of the NCS, see Ministry of Petroleum and Energy (2008).

Figure 3. NCS exploration and production



Source: Norwegian petroleum directorate.

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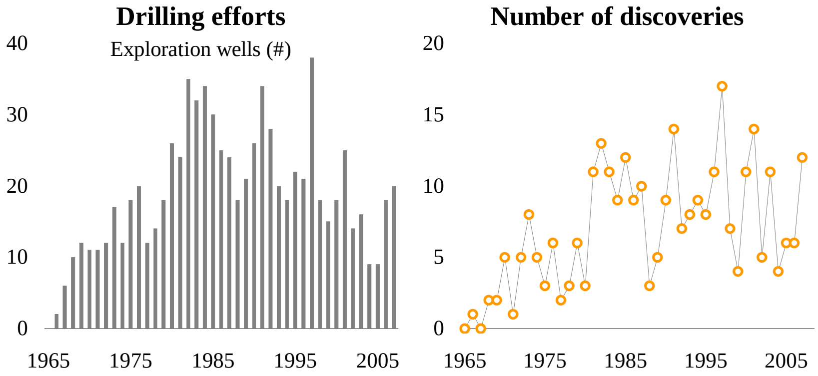
[7] A non-commercial discovery (Balder) was actually made by Exxon (Esso) already in 1967. However, it took 30 years of technological development to mature this discovery into a profitable field development project based on subsea templates tied back to a floating production and storage vessel. The Balder field was put on stream in 1999 and is still producing (mid 2008).

Regulated gradualism has been a guiding principle for the development of the Norwegian oil and gas sector. The key regulatory instrument for exploration and production is the production license, which gives the exclusive right for exploration and production of oil and gas within a specified area, usually referred to as a block. Production licences on the NCS are awarded through licensing rounds, and licensees retain ownership for the produced petroleum. A specific number of blocks are announced by government, and the companies prepare applications based on published criteria. Based on submitted applications, the Ministry of Petroleum and Energy (MPE) decide on a partnership structure for each license, and an operator is appointed to take responsibility for the day-to-day activities under the terms of the license. Typically, a production license is awarded for an initial exploration period that can last up to 10 years. However, specified obligation regarding surveying and/or exploration drilling must be met during the license period. At completion of this kind of obligations, licensees generally retain up to half the area covered by the licence for a specified period, in general 30 years.

After three decades of production, volume estimates from the Norwegian Petroleum Directorate (2008) indicate that 2/3 of the expected total physical oil and gas resources remain in the ground, nearly 40 per cent of total resources are yet to be matured to proven reserves and 26 per cent of total resources remain undiscovered. Exploration activity and results will be important to sustain production levels on the NCS over the longer term.

Figure 4. Exploration efforts and number of discoveries

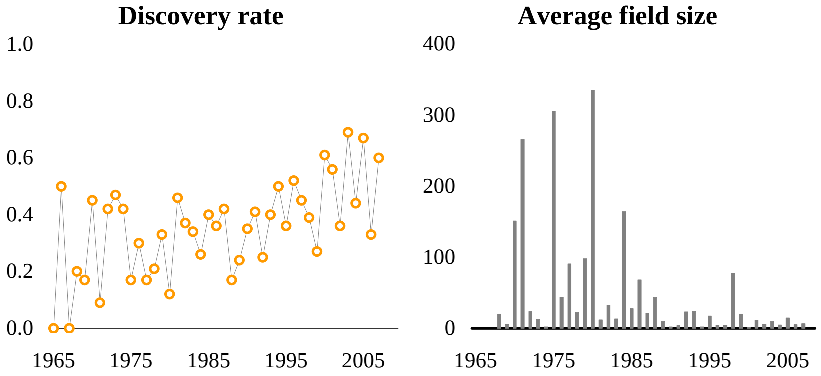


Source: Norwegian Petroleum Directorate and author's calculations.

The first exploration well was struck in the North Sea in 1966, but it took 30 wells and three years before the breakthrough was made with the discovery of the Ekofisk field late in 1969. Since then, another 1,200 exploration and appraisal wells have been drilled, of which some 850 are classified as exploration wells (cf . Figure 4). With more than 600 exploration wells, the North Sea represents approx. ¾ of total cumulated exploration activity on the NCS. 160 exploration wells have been drilled in the Norwegian Sea, whereas only 63 exploration wells have been drilled in the under-explored Barents Sea. As illustrated in the right-hand panel of Figure 4, the annual number of discoveries has largely hovered in the area between 5 and 15 over the last 20 years. However, we see a slight positive trend in the number of discoveries over time. To detect the sources and factors behind this development, the figures have to be decomposed even further.

A simple input measure to the exploration process is offered by exploration effort, or drilling activity, as illustrated in the left-hand panel of Figure 4. A corresponding output measure is offered by reserve additions per exploration well (yield per effort). However, exploration output can be decomposed even further, as reserve additions per exploration well is the product of average discovery rate and average field size. The historical record for these two indicators is illustrated in Figure 5. Over the 40-year period, the discovery rate has average 1/3, which is quite high by international standards. We also note that the volatility of the discovery rate was high in the early phase, which is an indication of high exploration risk due to of inadequate information and poor experience. Over time, however, discovery rates seem to have stabilised somewhat, and we also note a slight upward trend, which probably can be attributed to the accumulation of competence, experience, and technological progress.

Figure 5. Exploration success: discovery rates and average field size



Source: Norwegian petroleum directorate and author's calculations.

The right-hand panel of Figure 5 reports annual averages for the size of new discoveries. In their pursuit of maximum return, oil companies rank exploration prospects according to value potential, and target the structures with the highest potential first (Iledare, 1995; Dahl and Duggan, 1998). This is one explanation why the early phase of an oil province is usually dominated by large discoveries. However, government policies also played an important role for this development, as the early phase of the NCS history was characterised by regular licensing rounds, with a continuous supply of virgin exploration acreage with high potential.

Finally, the high oil price level and an overconfident oil price outlook may also have induced oil companies to increase their exposure to overall exploration risk in the 1970s and early 1980s. This would also imply (lower expected discovery rates, and) a higher expected field size.

Over the last years, the NCS has gradually entered a more mature phase. Exploration efforts have been weak over the last years, and reserve additions from exploration have slowed to a trickle (cf. Figure 3). Oil production has passed its peak, gas production is approaching its plateau, and there is no line of imminent new field developments. On the other hand, the record-high oil price provides a strong stimulus for investment to enhance recovery from producing fields. To sustain investment and production over the longer term, the NCS will ultimately depend on new reserve additions from exploration. Both authorities and companies see a high potential for gas discoveries in the deepwater areas off Mid Norway, but so far, the establishment of a proven exploration play for this area is still pending (Norwegian Petroleum Directorate, 2007).[8] Access to new exploration acreage with high potential in vulnerable waters off Northern Norway could be important to enhance the NCS reserve base. Due to environmental concerns, the issue of new awards in Northern Norway has developed into a highly controversial issue. However, an extrapolation of the Norwegian approach to petroleum management suggests that a political consensus will be reached, and that the industry will continue its gradual quest into Northern waters.

A simple model of NCS exploration

The reserve concept is one of the factors that distinguish non-renewable resource industries from other industries. Due to this defining characteristic, oil companies engage in extremely risky exploration activities to support and grow their base of oil and gas reserves, and to sustain production activity over the longer term. Among the oil companies, the set of exploration opportunities is subject to continuous evaluation and management based on a range of criteria relating to geology, technology, economic factors, and government policies. The result of this balancing act is a dynamic exploration strategy. Moreover, the implied portfolio of exploration drilling activities yields a certain average finding rate, a particular distribution of discovery size, and ultimately, a specific rate of gross reserve additions. Consequently, the data we observe for efforts and efficiency in oil exploration are formed by simultaneous decisions in each company. This simultaneity should be appreciated also in economic models of the exploration process.

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[8] An exploration play is a geographically bounded area where a combination of geological factors suggests that producible petroleum can be discovered. The three most important factors are 1) a reservoir rock where petroleum can be preserved, 2) a tight geological structure (a trap) that covers the reservoir rock, and 3) a mature source rock containing organic material that can be converted into petroleum (Norwegian Petroleum Directorate, 2007).

Drawing on Mohn (2008), an empirical modelling approach to exploration behaviour will now be outlined, along with some results for time series data from the NCS.

The exploration process represents the traditional source for reserve additions. Based on sophisticated insight on the underground, exploration wells are directed at various layers that presumably hold oil and/or gas resources, according to different exploration plays. Exploration drilling may take place in virgin areas, where undiscovered deposits are potentially, and where the base of accumulated information and experience is correspondingly small. Alternatively, companies may focus their exploration in areas where fields have already been developed, with a significant base of competence and experience, and with access to well-developed infrastructure for processing and transport. Exploration in frontier areas represents higher risk than in mature areas. Within the companies, this risk is balanced against expected return in the management of the total exploration portfolio.

Based on standard principles from neoclassical theory for producer behaviour, exploration activity may be represented by a standard production function, whereby inputs and technological progress are transformed into reserve additions. With profit maximisation as the key behavioural assumption, such a model transforms into an optimal supply plan, where expected reserve additions depend on the oil price (P_t) and a set of state variables for geology (depletion; H_t), technology (Z_t), and government regulation (E_t). Having tested a range of alternatives, our preferred model includes cumulated exploration drilling activity as a proxy for depletion (H_t). Over the years, the collection of seismic data has grown exponentially on the NCS, reflecting the accelerating diffusion of increasingly advanced techniques for more efficient exploration activities. Accordingly, seismic surveying activity (Z_t) is included among our explanatory variables to capture technological progress. Finally, exploration efforts and efficiency is influenced by the availability of exploration acreage, which is subject to government regulation. Consequently, our model also includes the volume of open exploration acreage (E_t), which will be influenced by both licensing rounds ($\Delta E_t > 0$) and relinquishments and license expiration ($\Delta E_t < 0$).

We also bear in mind that reserve additions do not depend solely on efforts, but also on output. To this end, we apply a useful decomposition introduced by Fisher (1964), who demonstrated that annual reserve growth (R_t) can be seen as the product of exploration effort (D_t), the average discovery rate (S_t), and average discovery size (M_t). With explanatory variables grouped in the vector $X_t = [P_t, H_t, Z_t, E_t]$, this yields for annual reserve addititions:

$$R(X_t) = D(X_t) \cdot S(X_t) \cdot M(X_t)\,. \tag{1}$$

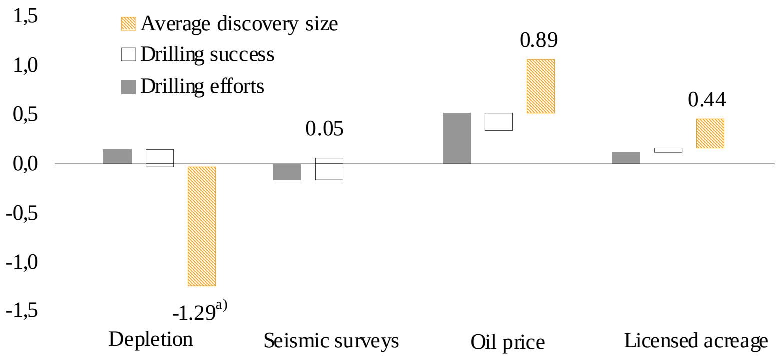
Equation (1) illustrates three sources of reserve additions, which all can be influenced by geology, technology, economics, and regulation. Consider the impact on reserve additions from an increase in the oil price. This will depend not only on how an oil price shock affects drilling activity (D_t), but also on its influence on the discovery rate (S_t) and average field size (M_t). The relation between these factors is again a result of the management of exploration portfolios within each oil company. To describe these mechanisms more precisely, define ε_P^R as the percentage increase in annual reserve additions caused by an oil price increase of one percent. Equation (1) now implies that this total elasticity can be represented by the sum of three partial elasticities:

$$\varepsilon_P^R = \varepsilon_P^D + \varepsilon_P^S + \varepsilon_P^M \ . \tag{2}$$

Thus, the impact of an oil price increase depends directly on how such an increase affects each of the three components of annual reserve generation. Corresponding elasticities apply for the other explanatory variables.

Applying simultaneous estimation techniques, Mohn (2008) now estimates the various elasticities implied by Equations (1) and (2). Specifically, the empirical model has three endogenous variables (D_t, S_t, M_t), and is specified as a vector error-correction model, whereby changes in dependent variables are regressed on changes in explanatory variables, as well as the deviation from an underlying equilibrium relation between the model variables. Estimation is based on Full-Information Maximum Likelihood (Johansen, 1995), as implemented in PcGive 10.

Figure 6. Decomposed elasticities of reserve-generation



Estimated partial and total elasticities by explanatory variable (per cent) [*)]

[*)] FIML estimates obtained with PcGive 10.

[a)] Semi-elasticity: percentage change in reserve generation from abs. change in depletion indicator.

Source: Mohn (2008).

Key results for persistent elasticities are summarised in Figure 6. The estimated long-term parameters illustrate the percentage impact on annual reserve additions from an increase in the explanatory variables of one per cent. Moreover, Figure 6 also illustrates how the combined elasticities of reserve growth with respect to explanatory variables may be decomposed, with partial attributions from drilling efforts (*D*), discovery rate (*S*), and average discovery size (*M*).

In terms of specific effects from explanatory variables, maturation and depletion (H_t) has a highly significant (p = 0.00)[9] dampening effect on annual reserve additions, according to the estimation results. The main mechanism for this process is that the average field size falls over time, which is also evident from Figure 5. Seismic surveying activity, our proxy for technological development, has as mixed effect on the exploration process. The estimated total effect of this variable on reserve additions is small, and statistically insignicant (p = 0.61). However, the results do imply that seismic surveying activities contribute significantly to the increase over time in discovery rates (p = 0.00), as indicated in Figure 5.

Results for the oil price (P_t) illustrate the richness in economic effects from the proposed modelling framework, with statistically significant parameter for all the involved partial effects, as well as for the total effect (p = 0.00). Reserve additions are stimulated by an increase in the oil price, not only because drilling activities are spurred, but also because of positive effects on exploration efficiency – or yield per effort. Discovery rates are suppressed when the oil price increases, according to the econometric results. On the other hand, the estimated model establishes a positive and highly significant link between the oil price and average discovery size, an effect which dominates the estimated reduction in the discovery rate. This is a clear indication that oil companies adjust their portfolio of exploration activities according to changes in economic and financial conditions (Reiss, 1990). In times of high oil prices, high cash-flows and high risk appetite, companies seem to tilt their exploration activities towards risky areas (frontier exploration), with relatively low discovery rates, and with high expected discovery size. When oil prices are low, cash flows are constrained, and the risk appetite is more modest, exploration strategies are typically more cautious. Consequently, exploration efforts are reduced, and focused in areas with higher discovery rates – and smaller expected field sizes (mature areas).[10]

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[9] In testing of statistical hypotheses, the probability value (p-value) of a parameter estimate represents the likelihood of obtaining a result as extreme as the one obtained through our estimation, given that the null hypothesis is through. In our notation (p = 0.00), the implication is not that the p-value of this parameter estimate is actually 0, but that it fails to break zero at the two-digit cutoff level of measurement.

[10] As opposed to frontier exploration areas, mature areas are typically characterized by proven exploration models, producing fields, well-developed infrastructure, transport facilities and market access. Moreover, exploration activities in these areas are usually directed at smaller satellite fields which can be tied back to already producing facilities of larger reservoirs (in decline), without the large investments involved by stand-alone field developments in new oil and gas regions (Norwegian Petroleum Directorate, 2007).

Finally, the estimated model for the exploration process on the NCS also provides a significant role for government policies, as represented by access to exploration acreage. An increase in total licensed exploration acreage of 1 per cent, will produce an increase in annual reserve additions by 0.44 per cent ($p = 0.00$), according to the results. This effect has two sources. First, a modest increase in drilling activity is sustained when new acreage is offered. Second, new licensing rounds have a positive effect on average discovery size. With drilling efforts focusing on the most prospective available blocks at any time, it is natural that new licensing rounds will result in higher average discovery size.

The presented model leaves the impression that variables relating to technology, economics and government regulation play a significant role for reserve additions on the NCS. Moreover, the outlined modelling approach provides a better representation of the complexity and sophistication the exploration process than a simple geophysical approach. Consequently, the study by Mohn (2008) lends substantial support to the hypothesis that economic variables contribute to the explanation of oil exploration and production behaviour. To illustrate this point more candidly, the presented model is re-estimated with the depletion indicator (H_t) as the only explanatory variable.

Table 1. The contribution of economic variables to overall model quality

Test statistics for model reduction

	LL	*SC*	*HQ*	*AIC*
Presented model	26.50	0.42	-1.20	-0.47
Reduced model	-2.88	0.86	0.66	0.55

Table 1 reports the implied changes in estimated model quality, evaluated through the log-likelihood ratio (*LL*), as well as the Schwartz (*SC*), Hanna-Quinn (*HQ*), and Akaike information (*AIC*) criteria. These latter three criteria of model selection may be seen as goodness-of-fit measures for comparisons of different time series models based on the same data set. See Dornik and Hendry (2001) for theoretical background, technical detail and specific procedures for standard specification tests and model diagnostics in PCGive 10. At this point, we remind that an increase in the log-likelihood ratio (*LL*) is an indication of improved statistical power of the model, whereas a model improvement is generally associated with a reduction in the three other reported test criteria for model selection (*SC*; *HQ*; *AIC*). From Table 1 we clearly see that a disregard of economic variables yields a reduction in the log-likelihood, and increase in the other criteria of model selection. This confirms the preference for a combined model, and an appreciation of economic variables in the exploration process.

A simple model of NCS production

Previous research on oil and gas production suggests that economic variables may also improve the explanation of production activity. To test the impact of economic variables on extraction levels, Moroney and Berg (1999) propose and estimate a simple econometric model on data from the United States. Not surprisingly, they find that a combination of economic and geophysical variables provide an explanation which outperforms its alternatives, both in economic and statistical terms. Based on the framework of Moroney and Berg (1999) a model will now be outlined to perform a similar test on production data from the NCS (cf. Figure 3).

As in the previous section, we first specify a model that contains both physical and economic variables. We then remove the economic variables, and compare the two model versions using both economic interpretation and statistical criteria of model selection. Consider a competitive firm that produces oil according to a well-behaved neo-classical production function $Q = F(L, H)$,[11] where L_t represent a vector of variable inputs and H_t is a vector of state variables, including reserve variables, technological conditions and government policy. Maximisation of profits (Π) now implies that the following restricted profit function can be derived:

$$\begin{aligned} \Pi = \Pi(P, W, H) &= \max_{Q,L} \{P \cdot Q - W \cdot L\} \\ s.t.\ F(L, H) &\geq Q \ , \end{aligned} \tag{3}$$

where P is the price of oil, and W is the vector of input prices. Previous literature suggests that the role of traditional inputs is dominated by other factors in the process of oil and gas exploration and production (e.g., Dahl and Duggan, 1998; Farzin, 2001; Mohn, 2008). The attention of this modelling exercise will therefore be focused on potential variables of the H vector, and the vectors of variable inputs and their prices are neglected for simplicity of exposition.[12] In this example, we are especially concerned with the role of economic variables (P) as opposed to geological variables. Consequently, the H vector of this sketchy application will therefore be earmarked for variables of reserve development and depletion.

In our approximation of an empirical specification for oil production, we now assume a multiplicative form for the restricted profit function:

$$\Pi = \Pi(P, H) = \tilde{A} P^{\tilde{\alpha}} \exp[\beta H + \gamma H^2], \tag{4}$$

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[11] With a long-term perspective on the production process, all inputs may be seen as variable. Consequently, the capital stock can be included in both the L and the H vector, depending on the horizon of the decisions in question.

[12] To test the validity of this assumption, a variety of interest rate and labour cost variables were included in preliminary estimations. However, plausible and robust estimates could not be established for any of their coefficients.

Observe that a squared term is included for the depletion mechanism, to allow for potential non-linearities in the process of resource exhaustion. Hotelling's lemma now allows the derivation of optimal oil supply directly from Equation (4). Partial differentiation with respect to the oil price now yields:

$$\frac{\partial \Pi}{\partial P} = AP^{\alpha} \exp[\beta H + \gamma H^2] \tag{5}$$

where $A = \tilde{\alpha}\tilde{A}$ and $\alpha = \tilde{\alpha} - 1$, H_t is a depletion indicator, proxied by accumulated production, and α, β, and γ are the coefficients to be estimated.

Introducing small-caps for natural logs, as well as a time index *t*, we now specify the econometric model as a simplified error-correction representation of Equation (5):[13]

$$\Delta q_t = \lambda q_{t-1} + b_0 p_{t-1} + b_1 H_{t-1} + b_2 H_{t-1}^2 + u_t \tag{6}$$

The underlying structural parameters of Equation (3) can be calculated directly from the estimated parameters of Equation (6).[14] The lag structure of Equation (4) implies a gradual adjustment to oil price changes which is consistent with adaptive price expectations (cf. Farzin 2001). A simple form of expectations formation is therefore encompassed by the error-correction specification. This specification also removes problems due to non-stationarity in the model variables, and secures dynamic balance among variables in the econometric equation. Equation (6) may therefore be estimated by ordinary least squares.

Based on annual time series data over the period 1972-2004, we obtain:

$$\Delta \hat{q}_t = \underset{(0.00)}{-0.41 q_{t-1}} + \underset{(0.00)}{0.38 p_{t-1}} + \underset{(0.00)}{0.95 H_{t-1}} - \underset{(0.00)}{0.19 H_{t-1}^2} \tag{5}$$

The estimated model is well-behaved, and meets the requirements implied by standard specification tests. All parameters are highly significant in statistical terms, as indicated by the p-values (in brackets). The lagged production level exerts a negative influence on production growth, according to the estimated model, implying a slowdown in production as long as production increases. Observe also that our depletion indicator takes a positive coefficient, suggesting that production growth is actually stimulated by cumulated production. However, this stimulation is modified by the negative and highly significant coefficient on the squared depletion term. In sum, the standard properties of the geophysical approach seem to

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[13] The error-correction specification would normally also include changes in model variables. However, these proved insignificant in preliminary estimations, and are therefore left out for simplicity of exposition. The constant term is also removed for the same reason.

[14] Letting all changes approach zero, Equation (4) can be solved for q_t to obtain $\alpha = -b_0/\lambda$, $\beta = -b_1/\lambda$, $\gamma = -b_2/\lambda$ (Bårdsen, 1989).

be fairly well captured by Equation (5). Observe also that the oil price takes a positive coefficient. This indicates that production levels on the NCS are significantly influenced by this key economic parameter. To study the contribution of economic variables to our explanation of NCS production growth, we now reestimate the model, leaving out the price of oil. This yields:

$$\Delta\hat{q}_t = \underset{(0.30)}{0.05} q_{t-1} - \underset{(0.61)}{0.17} H_{t-1} + \underset{(0.33)}{0.03} H_{t-1}^2 \tag{6}$$

The first impression is already that Equation (6) provides a quite miserable explanation of production activity compared Equation (5). All parameters approach zero, they change signs, and none of them are significant in statistical terms.

Table 1. The contribution of economic variables to the production model

Test statistics for model reduction

	LL	*SC*	*HQ*	*AIC*
Model with oil price	0.77	0.38	0.26	0.20
Model without oil price	-19.21	1.48	1.39	1.35

The standard criteria of comparison is the squared multiple correlation coefficient R^2. However, as the constant term was removed from our preferred model based on statistical inference, R^2 is no longer well-defined.[15] The equation standard error provides a better statistic for model comparison, as this measure is adjusted for degrees of freedom. For Equation (5), we obtain an equation standard error of 0.25, whereas the corresponding estimate for Equation (6) is 0.45. This suggests a clear preference for the model represented by Equation (5). To conclude even more rigorously, Table 2 compares the common battery of specification tests for statistical performance. As for the exploration models in the previous section, Table 2 reports changes in estimated model quality, evaluated through the log-likelihood (*LL*), as well as the Schwartz (*SC*), Hanna-Quinn (*HQ*), and Akaike information (*AIC*) criteria. These indicators are the same as applied for the exploration model above. See Dornik and Hendry (2001) for details on their properties. We remind that an increase in the log-likelihood ratio (*LL*) is an indication of improved statistical power of the model, whereas a model improvement is generally associated with a reduction in the three other reported test criteria for model selection (*SC*; *HQ*; *AIC*). Again, we see that a disregard of economic variables yields a

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[15] R^2 also has a range of weaknesses with respect to model evaluation. The inclusion of additional variables will never reduce the value of R^2, and it may improve even if nonsense variables are adjoined. Moreover, R^2 also depends on the choice of transformation of the dependent variable (for example, Δy versus y). R^2 may therefore be misleading for model evaluation purposes.

substantial reduction in the log-likelihood, and increase in the other criteria of model selection. Consequently, we should prefer a combined model. In summary, the value and importance of economic variables in models of petroleum activity is further corroborated.

Concluding remarks

Empirical research in petroleum economics has demonstrated again and again that predictions based on the geophysical approach to oil exploration and production gives a poor representation of actual development of the last 50 years or so. The typical pattern for individual fields, regions and provinces is that exploration activities uncover far more oil reserves than is thought possible in the initial estimates. Moreover, the accumulation of technology, experience and competence also makes it possible to recover more oil from each producing field than implied by the static traditional geophysical approach to oil extraction.

My two applications are based on data from the Norwegian Continental Shelf, an oil province whose development is characterised by gradualism and government regulation. New insights into the complex process of oil exploration are obtained through the combination of physical and economic variables in an integrated dynamic time series model. As an example, the results imply that additions to the reserve base is affected by the oil price, not only because drilling efforts are spurred when the oil price increases, but also because the output of the drilling process is influenced by prices, cash-flows and adjustments to the exploration portfolio in each company. The presented model of NCS oil exploration suggests that companies increase their exposure to exploration risk when the oil price goes up, yielding lower discovery rates, and higher average discovery size. On the other hand, a reduction in the oil price makes oil companies more cautious. A low oil price makes them focus exploration activities in less risky (mature) areas. The result is higher discovery rates, and smaller discoveries. In the same model, reserve depletion exerts a dampening effect on reserve growth, partly offset by the positive impact of seismic suveys on discovery rates. Through the design and execution of licensing rounds and awards of new exploration acreage, the expected reserve and production potential on the NCS is also affected by government policy. Awards of new exploration acreage give a stimulus to reserve additions due both to enhanced drilling efforts and improved drilling efficiency, according to the results.

A simple econometric example for NCS oil production also suggests that economic variables play a significant role in the explanation of production levels. The preferred econometric model of oil supply includes a positive and highly significant parameter for the real oil price, indicating an own-price elasticity of oil supply above 0.9, which is high by comparable standards. As for the exploration model, we also find the estimated model of production to deteriorate when this simple economic parameter is left out of the equation. A variety of specification tests and standard statistics of model fit and clearly suggest that simple geophysical models are outperformed by models which also include economic variables.

In summary, modern economic research has established a firm role for economic variables in models of oil exploration and production. The importance of technology, economics and policies to supplement the geophysical aspects of oil production is also supported by the two examples of this chapter.

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