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**Abstract:**
We perform an empirical analysis of the extent to which ongoing technological change through R&D activity has offset the effect of ongoing depletion on the cost of finding additional reserves of oil in eight global regions. We introduce a finding cost function that among other factors depends on the cumulative number of past R&D expenses and cumulative past production, measuring technological change and depletion, respectively. For all our regions we find significant effects of both depletion and technological change on oil finding costs from 1981 to 2009, barring cyclical variations in finding costs that could come from changes in factor prices. For almost all regions technology more than mitigated depletion until around the mid-nineties. However, we find that depletion outweighed technological progress over the last decade.

**Keywords:** Oil, depletion, technological change, R&D, finding costs

**JEL classification:** L71, Q31

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## Sammendrag

Vi utfører en empirisk analyse som ser på i hvilken grad den pågående teknologisk fremgangen gjennom FoU-aktivitet har motvirket uttømmingseffekten på lete- og utviklingskostnadene for olje i åtte regioner. Vi introduserer en lete- og utviklingskostnadfunksjon som blant annet avhenger av akkumulerte FoU-utgifter og akkumulert produksjon i tidligere perioder, som henholdsvis måler den teknologisk fremgangen og uttømmingseffekten. For alle regionene finner vi signifikante effekter av både uttømming og teknologisk endring på lete- og utviklingskostnadene for olje fra 1981 til 2009, mens vi holder endringer i disse kostnadene som skyldes endringer i faktorpriser utenfor. For alle regioner var den teknologiske fremgangen sterkere en uttømmingseffekten frem til midten av nittiårene. Over det siste tiåret var effekten av uttømming sterkere enn teknologisk fremgang.

# 1. Introduction

Finding petroleum is characterized by both increasing knowledge as well as diminishing reserves. Increasing knowledge through research and development (R&D) activity leads to advances in technology that improves the productivity of the finding process (i.e., exploration and development (E&D)). Technological advances such as e.g. three-dimensional seismology and horizontal drilling are widely acknowledged to have had significant impact on productivity in the E&D process, reducing finding costs over time. At the same time, ongoing production depletes the resource base. Investments first target the most profitable oil reserves, leaving remaining resources in remote or expensive regions. Extracting oil from fewer and poorer prospects diminishes the returns to E&D, and increases finding costs (Adelman, 1993).

This paper studies the impact of depletion and offsetting technological change on finding cost for oil worldwide. We focus on the E&D activity where the effects of depletion and technological growth first exert an impact on the cost of getting petroleum products to the customers (Cuddington and Moss, 2001). The issue of scarcity is better understood within the context of exploration and development costs rather than the often-used extraction costs (Reynolds, 1999).

Many regions experienced a decline in finding costs from around 1980 towards the end of the 1990s. In the early 1980s high oil and gas prices supported relatively expensive E&D projects. The price decline in the following years forced producers to reduce finding costs in order to stay competitive (Fagan, 1997). Increased knowledge in computer technology, geophysics and drilling were important cost-saving factors. From around 2000 finding costs started to increase in most regions, above all after 2004. This increase in finding costs went along with a surge in factor prices. Costs of raw materials grew in line with increased demand from emerging economies (Cambridge Energy Research Associates, 2008). Costs of e.g. hiring rigs rocketed along with increased activity following the surge in oil price.

Barring cyclical variations in oil finding costs that could come from variations in factor prices, our research questions are:

- -What portion of the cost variations can be attributed to technological progress?
- -What has been the magnitude of the countervailing effect of depletion?

Various studies have described the race between resource depletion and technological change in the petroleum industry. However, they differ above all in what proxies they apply to measure these two

opposing effects. Fagan (1997) applies data for 27 large U.S. oil producers from 1974 to 1994. Depletion is measured as cumulative wells drilled and a time trend captures the technological change. She finds that an accelerating rate of technological growth reduced average finding costs 15 percent (onshore) and 18 percent (offshore) per year by 1994. Resource depletion increased cost at an average annual rate of 7 percent onshore and 12 percent offshore. Thus, the effect of technological progress outweighed that of depletion over the period.

Forbes and Zampelli (2000) examine success rates in exploratory drilling in the Gulf of Mexico from 1978 to 1995 using data from 13 large producers. They find that the small increases in the success rate from the early 1980s to 1995 were largely due to a substantial decline in the price of petroleum, discouraging firms from pursuing less promising prospects. Prior to 1985 the net effect of technological progress on depletion was very small. However, after 1985 technological progress resulted in an annual rate of 8.3 percent growth in the success rate of finding petroleum.

In empirical analysis a time trend has been widely used as a proxy for technological progress, since it is usually difficult to construct variables capturing the dynamics of technological change. There are exceptions, though. Cuddington and Moss (2001) introduce a measure of the cumulative number of technological innovations in the petroleum sector. They find that technological progress played a major role in allaying what would otherwise have been a sharp rise in the average cost of finding additional petroleum reserves in the USA over the 1967-1990 period, and that this effect was stronger for gas than for oil. Managi *et al.* (2004) apply a micro-level data set from the Gulf of Mexico over the 1947-1998 period. They suggest different proxies for technological change in the exploration stage, and find that the rapid pace of technological change outpaced depletion and productivity increased rapidly, particularly in the most recent 5 years of their study.

The above mentioned studies have all discussed the opposing effects of technological change and depletion in North-America. To our knowledge, our study provides the first empirical evidence on this issue on a global scale. Secondly, we have not found other studies that cover the last decade. In addition, in line with Fagan (1997) but contrary to many other studies, we take changing factor prices into consideration. The cost increase in drilling seen worldwide in recent years has likely been one of the major factors behind the increase in gas and oil prices over the last decade (Osmundsen *et al*, 2012a). In addition there has been a huge price increase for many important raw materials, e.g. steel. According to Cambridge Energy Research Associates (2008) it was above all increasing metal prices and rig rates that led to rocketing costs in the petroleum industry after 2004. Lastly, in our study we

apply R&D as a proxy for technological change as opposed to the above mentioned studies. We apply cumulative output as a proxy for depletion.

Section 2 derives the model and Section 3 presents the data. Section 4 provides the estimation results and a subsequent discussion. Section 5 concludes.

# 2. The model

The first step of supplying petroleum to the market is E&D to locate and develop additions to the stock of proved reserves. The amount of new reserves in period *t*, $Q_t$, might be thought of as dependent on the traditional input factors; land, labor and capital. Due to lack of data for these variables covering the oil sector in eight regions worldwide, we have instead identified two important input factors; rig activity and steel. Drilling costs can represent more than half of the development cost of an offshore petroleum field (Osmundsen *et al*, 2012b). In addition, steel is an important raw material in the oil sector. We let the amount of new reserves $Q_t$ be generated using a Cobb-Douglas type of production technology:

$$(1)\quad Q_t = R_t^{\alpha_1} S_t^{\alpha_2} F\left(\sum_{s=0}^{t-j} RD_s, \sum_{s=0}^{t-1} Q_s\right)$$

where *R* and *S* are inputs of rig activity and steel, respectively. F is a function of both cumulative past expenses on R&D activity ($RD_{t-j}$), where j counts the lag in years, and cumulative past additions to new reserves ($Q_{t-1}$). We let $F'_{RD} > 0$, as increased technological progress through past R&D activity leads to increased current reserve additions. Romer (1990) describes new technology as designed and produced by a profit-maximizing research and development sector. Technological advances through R&D activity such as three-dimensional seismic techniques, horizontal drilling and offshore platforms capable of operating in deep-water environments are widely acknowledged to have had significant impact on the cost of E&D (Cuddington and Moss, 1998). In addition, new technologies in platform design have led to reductions in development costs, as well as an increase in reserve additions (EIA, 2012a). In our modeling of technological advances we disregard depreciation with respect to the level of technology. Further, we let $F'_Q < 0$, as it is standard in the resource economics literature to assume that current reserve additions also depends negatively on cumulative past additions to reserves (Fagan, 1997). This captures the resource depletion effect and means that reserves will be discovered in order of their quality and ease of accessibility.

Assuming constant returns to scale (see below) and that exploration and development firms minimize the cost of a given level of reserve additions $Q_t$, we get the following finding cost function:

$$(2)\ \ C_t = C_0 p_{Rt}^{\alpha_1} p_{St}^{\alpha_2}\, G\left(\sum_{s=0}^{t-j} RD_s, \sum_{s=0}^{t-1} Q_s\right) Q_t\, e^{\mu_t}$$

where the constant $C_0$ is a function of the underlying production function parameters. $P_R$ is the price of hiring oil rigs and $P_S$ is the steel price. $G$ is a function assuming that technological growth leads to lower costs ($C'_{RD} < 0$) and increased past reserve additions result in higher costs ($C'_Q > 0$). $\mu_t$ is the error term.

We emphasize that total cost of finding additional reserves depends positively on both (i) the current rate of new reserve additions $Q_t$ and (ii) cumulative past additions via the resource depletion effect. As we only have complete data on average finding cost (and not separate data on total finding costs and the amount of current additional reserves), it is necessary to assume constant returns to scale[1], as we did with respect to Eq. (2). Dividing both sides with $Q_t$, we get the average finding cost function:

$$(3)\ \ \overline{C}_t = C_0 p_{Rt}^{\alpha_1} p_{St}^{\alpha_2} G\left(\sum_{s=0}^{t-j} RD_s, \sum_{s=0}^{t-1} Q_s\right)\ e^{\mu_t}$$

Due to the lack of data for cumulative past reserve additions over the period, we apply cumulative production as proxy for the depletion effect[2].

$$(4)\ \ \overline{C}_t = C_0 p_{Rt}^{\alpha_1} p_{St}^{\alpha_2} G\left(\sum_{s=0}^{t-j} RD_s, \sum_{s=0}^{t-1} X_s\right)\ e^{\mu_t}$$

where $X_s$ is production. However, production or cumulative capacity also measures learning-by-doing (Arrow, 1962). Hence, this variable captures the net impact of two separate effects: depletion, which

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[1] We have not data to identify a complete Cobb-Douglas production function with respect to input factors as land, labour and capital. Hence, it is difficult to assess what kind of restrictions the assumption of constant returns to scale imposes on the parameters in the production function in Eq. (1) and Eq. (6) below.

[2] We tried to apply data on proved reserves from BP (2012) and EIA (2012b). However, the data for many regions were of too poor quality for our purpose. The value of proved reserves was often constant over several years for some countries.

should impact costs positively, and the "learning curve" effect, which should impact costs negatively. If $G'_X > 0$ in Eq. (4), this entails that depletion is the dominating effect, which is assumed in the resource extraction literature (Siegel, 1985).

We assume that the G-function is linear in its arguments. We let the level rather than the log of cumulative R&D expenses and cumulative production enter the log average finding cost function as this turns out to give somewhat more precise parameter estimates:

$$(5)\quad \ln \overline{C}_t = \alpha_0 + \alpha_1 \ln p_{Rt} + \alpha_2 \ln p_{St} + \alpha_3 \left( \sum_{s=0}^{t-j} RD_s \right) + \alpha_4 \left( \sum_{s=0}^{t-1} X_s \right) + \mu_t$$

where $\ln C_0 = \alpha_0$. We have $r$ regions. We have regional data on finding costs and cumulative production. We let the steel prices be equal across regions.[3] Likewise, we introduce a world average rig rate as our data indicate that rig rates move in tandem across regions.[4] We apply total cumulative R&D expenses over all regions ($RD_{total}$) be a measure of the level of technology (with a lag of $j$ years), assuming spillover effects across regions (and we will discuss this assumption in Section 3).

$$(6)\quad \ln \overline{C}_{r,t} = \alpha_{0,r} + \alpha_1 \ln p_{Rt} + \alpha_2 \ln p_{St} + \alpha_3 \left( \sum_{s=0}^{t-j} RD_{total,s} \right) + \alpha_{4,r} \left( \sum_{s=0}^{t-1} X_{r,s} \right) + \mu_t$$

We specify Eq. (6) in real terms by applying a price deflator. Regarding the expected signs of the regression coefficients $\alpha_1$ and $\alpha_2$ is presumably positive, as increases in rig rates and steel prices should increase finding costs. $\alpha_3$ is a priori negative, reflecting that increased R&D expenses lead to improvements in technology, which in turn reduce average finding cost. $\alpha_4$ is presumably positive as increased production depletes the reserve base and increases costs.

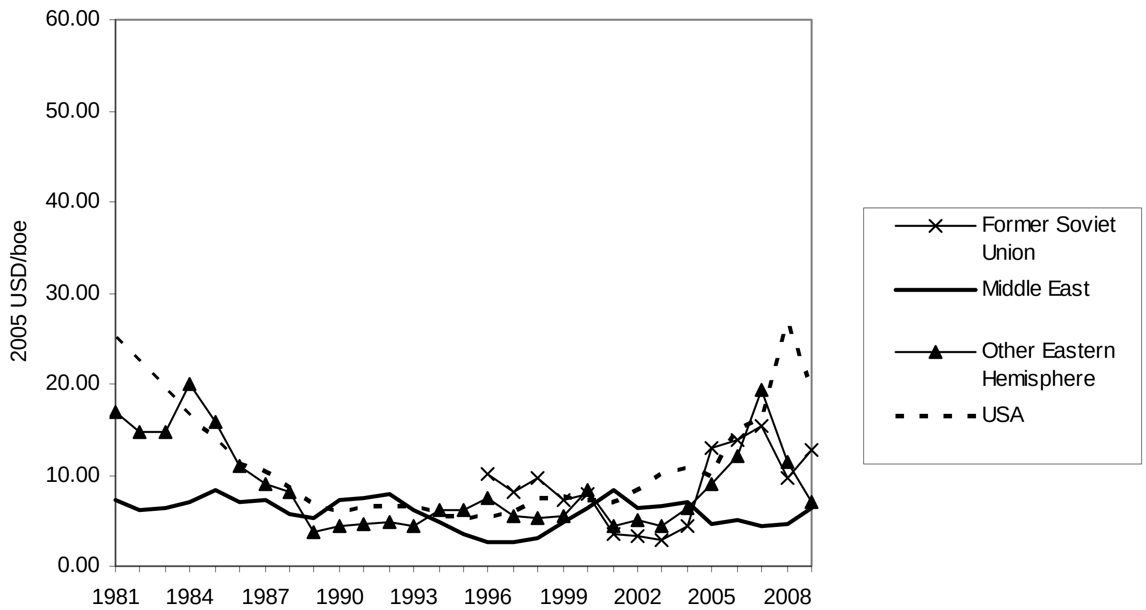
[3] A weaker, but possible assumption is that steel prices have regional differences in levels, but show a proportional development. Let the steel price in region $r$ be proportionate to the average steel price: $P_{St,r} = \lambda_r P_{St}$. We get by taking the logs: $\alpha_2(ln\lambda_r + lnP_{St}) = \alpha_2 ln\lambda_r + \alpha_2 lnP_{St}$ , where the first term on the right-hand side of the last equation is a part of the constant term.

[4] We do not have complete series on regional rig rates.

# 3. The data

The panel data on finding costs are from EIA (2012a)[5] and are average finding costs for oil and gas. We discuss to what extent these costs for U.S.-based companies operating worldwide reflect regional oil finding costs in Section 4. The data cover the regions: Other Eastern Hemisphere (India, China, Australia, and Other Asia), Africa, Former Soviet Union, Other Western Hemisphere (Central and South America), Europe, Canada, USA and the Middle East. We see from Figure 1 and 2 that the average finding costs decline for most regions up to around 1995-2000, and then starts to increase. Costs in 2009 are lower than the costs in the 1-3 preceding years for most regions. Finding costs are lowest in the Middle East, and the various regions alternate in being the highest cost region over the period.

**Figure 1. Regional average finding costs for Former Soviet Union, Middle East, Other Eastern Hemisphere and USA. 2005 USD/boe**

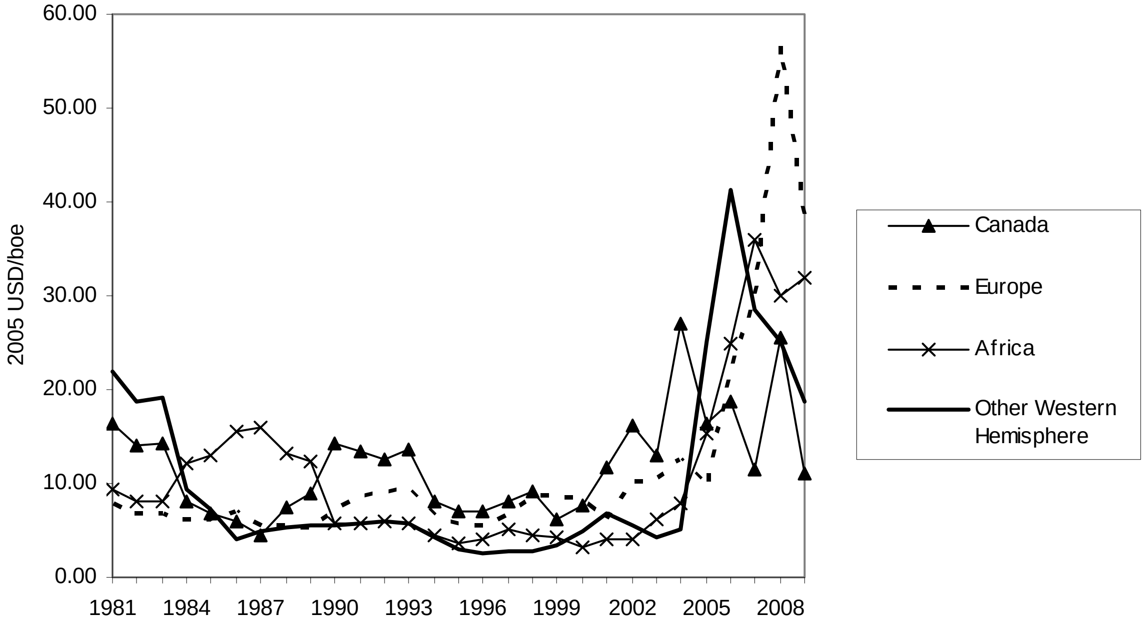



Source: EIA (2012a)

[5] A panel of major U.S.-based petroleum producers submits various annual data to the EIA. Excluding dry holes these companies drilled almost 18 000 exploratory and development oil wells worldwide in 2008, of which around 2500 were in USA.

Finding costs are defined as the cost of exploration and development (excluding expenditures for proven acreage) divided by additions to reserves (excluding net purchases of reserves). Finding costs are calculated as 3-year weighted averages, to smooth out volatility in discoveries, and reduce the lag between drilling and the booking of associated reserve additions, i.e. finding costs in 2009 are a 3-year weighted average over the 2007-2009 period.

**Figure 2. Regional average finding costs for Canada, Europe, Africa and Other Western Hemisphere. 2005 USD/boe**




Source: EIA (2012a)

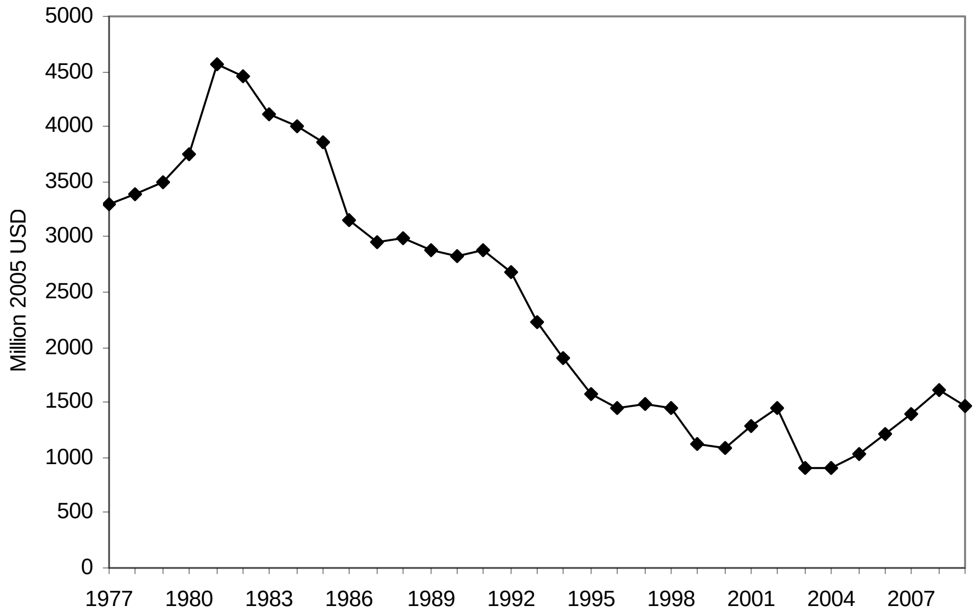
Data for regional production are from BP (2012) and measure cumulative output from 1965 (see Figures 1A and 2A in the Appendix).

The panel data on R&D expenses in the petroleum sector are also from EIA (2012a) and start in 1977. R&D expenses are total worldwide expenses for all major energy producers directed to the petroleum activity. Sources for the funding are both federal government, internal company and others. Assuming spillover effects between the oil companies so that the different regions can acquire the same technology, we let total R&D expenses over all regions be a measure of technological change (with a time-lag of *j* years) for each region (see Figure 3)[6]. We assume spillover of technological innovations because knowledge can be seen as a non-rivaled and to some extent a non-excludable good with sometimes minimal transaction costs. Therefore, once new knowledge has been developed it may be difficult to prevent dispersion to competing firms. Dispersion can occur because firms observe each other's products or production methods, or because workers change their place of employment. We find empirical support for our assumption of spillover effects by Wieser (2005). He surveys the literature and finds strong positive effects of intra-industry spillovers generated by firms above all in the USA.

[6] In addition, data on regional R&D expenses are withheld by the EIA to avoid disclosure.

We see that total expenses on R&D increase from 1977 to 1981, and then generally is on a declining trend up to 2000. Thereafter the development shows a mixed pattern, but expenses are higher in the 2007-2009 period than in 2000.

**Figure 3. Total R&D expenses. Million 2005 USD**



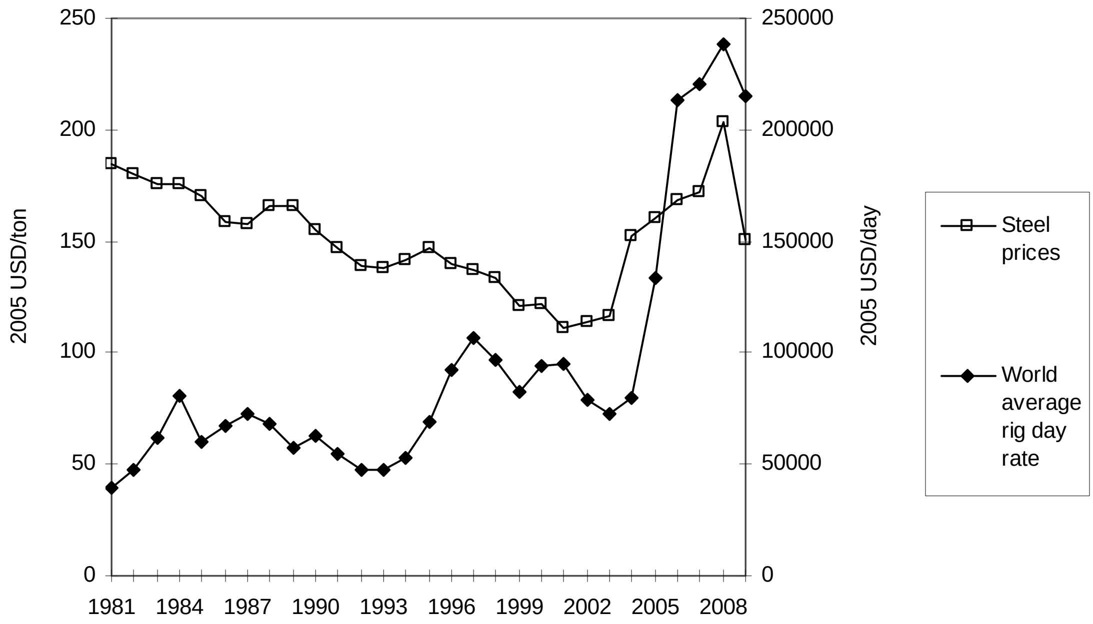

Source: EIA (2012a)

Factor prices include rig rates and steel prices (see Figure 4). Steel prices are from USGS-USGeologicalSurvey (2012). We see that the steel prices are generally declining from 1981 to 2001. Then the prices increase, although they drop in 2009.

Rig rates are from international offshore broker R.S. Platou, and are world average rig day rates of floater and jack-up rigs. Hence, we assume that the development in these offshore rig rates move in tandem with the onshore rig rates. The rig rates vary over the 1981-2004 period, but are on a mildly rising trend. The rig rates start to surge in 2004 and are almost three times higher in 2008 than in 2001. Following the financial crises in 2008 the rig rates decline somewhat in 2009.

All time-series are in real terms applying the US GDP Price Deflator (Bureau of Economic Analysis, 2012), see Figure 3A in the Appendix.

**Figure 4. Steel prices. 2005 USD/ton. World average rig rate. 2005 USD/day**




Source: USGS (2012): Steel prices, R.S. Platou: Rig rates

# 4. Estimation results and discussion

This section reports our estimation results of the average oil finding cost function in Eq. (6) for eight regions over the 1981-2009 period. The data are organized as a panel data with joint regional variables for R&D expenses, log steel prices and log rig rates. The model was estimated using linear regression for panel data applying the TSP software (TSP, 2005), with dummy variables to capture regional-specific fixed effects. Table 1 shows the estimates.

The model has a reasonable goodness of fit with adjusted R-square of 0.56. The reported standard errors are robust with respect to both heteroscedasticity and serial correlation in the residuals. The signs of the estimated coefficients are those predicted by theory.[7] There are significant regional net resource depletion effects with p-values of less than one percent, except for the Former Soviet Union which is significant at the 5 percent level.[8] The cost-increasing effect of depletion varies between the regions. The effect is strongest for Canada and Europe, which both can be regarded as mature

[7] Estimations were also performed for each region. The regional estimated coefficients had the right signs. However, the results were often not significant due to small samples.

[8] This is the only region with data for a shorter time period, i.e.1996-2009.

petroleum regions with relatively small reserves.[9] The depletion effect is smallest for the Middle East, which seems reasonable as the region has large resources that can be extracted at generally low costs. Hence, our results indicate that past production shifts the current average cost function upward because of the depletion effect. In addition, cumulative R&D expenses lagged 3 years are significant at less than 1 percent in our model. This means that R&D effort leads to improvements in technology that lowers the average finding costs for oil. In addition, higher steel prices and rig rates lead to increased average finding costs, but only the former is significant at a the 1 percent level [10].

**Table 1. Estimation results of the finding cost model in Eq. (6)**

| Variable | Estimate | t-value[1] |
|---|---|---|
| Intercepts: | | |
| $\alpha_0^{FSU}$ | -3.383 | -2.243 * |
| $\alpha_0^{OWH}$ | -5.497 | -3.961 ** |
| $\alpha_0^{AFR}$ | -5.470 | -3.939 ** |
| $\alpha_0^{OEH}$ | -4.550 | -3.238 ** |
| $\alpha_0^{EUR}$ | -4.993 | -3.443 ** |
| $\alpha_0^{CAN}$ | -5.216 | -3.779 ** |
| $\alpha_0^{USA}$ | -5.733 | -4.414 ** |
| $\alpha_0^{ME}$ | -5.274 | -3.886 ** |
| Cumulative past production: | | |
| $\alpha_4^{FSU}$ | 0.012 | 2.312 * |
| $\alpha_4^{OWH}$ | 0.031 | 4.794 ** |
| $\alpha_4^{AFR}$ | 0.036 | 4.639 ** |
| $\alpha_4^{OEH}$ | 0.026 | 3.162 ** |
| $\alpha_4^{EUR}$ | 0.068 | 6.197 ** |
| $\alpha_4^{CAN}$ | 0.116 | 4.894 ** |
| $\alpha_4^{USA}$ | 0.025 | 3.554 ** |
| $\alpha_4^{ME}$ | 0.009 | 3.215 ** |
| | | |
| $\alpha_3$ (3-year lag)[11] | $-0.358 \cdot 10^{-4}$ | -3.767 ** |
| $\alpha_1$ | 0.110 | 0.561 |
| $\alpha_2$ | 1.165 | 3. 627** |

$R^2$ (adjusted) 0.557

Total number of observations: 217. Estimation period: 1981-2009

[1] These are robust t-values as the standard errors are corrected for heteroscedasticity and serial correlation in the residuals.
** Significant at 1 percent
* Significant at 5 percent

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[9] Oil sands is not included in the Canadian data

[10] Including rig rates increases the explanatory power of the model.

[11] The 3-year lag gave the highest t-value, although not far from the 2- and the 3-year lag. Letting a linear time trend represent technology instead of R&D expenses, the reduction in costs is around 10 percent per year. With a time trend the regional depletion effects increase by 25-50 percent

We also compare the cost-lowering effect of technological change with the cost-increasing effect of depletion over the sample years, applying the estimated coefficients reported in Table 1, i.e. for constant rig rates and steel prices. The annual reduction in costs due to R&D activity increases from 12 percent in 1981 to almost 16 percent in 1985 and then generally declines to 4 percent at the end of the period. At the same time the annual increase in costs due to depletion rises over the period for all regions except the USA. For most regions technology more than mitigated depletion until around the mid-nineties (1995-97)[12] and from then on the depletion effect outweighed the impact of technological growth. Firstly, our analysis provides empirical evidence of the common claim that technology largely counteracted increasing resource scarcity in the American oil industry until the mid-nineties (Cuddington and Moss, 2001). As indicated in the introduction, various studies have found that ongoing technological improvements have largely, or at least partially, offset increasing resource scarcity during this period. Secondly, we find that this result applies to all regions worldwide over the same period. Thirdly, we find that depletion outweighed technological progress over the last decade for all regions, barring increases in finding costs that could come from changes in factor prices.

Our results indicate that the decline in finding costs in the USA (and other regions) due to technological growth was around 10 percent *in 1994*. This is lower than Fagan (1997), who found that the rate of technological change was 15 percent offshore and 18 percent onshore in 1994 in the USA. She used a time trend and not R&D activity as a proxy for technological growth.[13] In addition, our results indicate that the average measure of the rate of depletion in the USA was around 9 percent over the 1981-1994 period. This is more in line with Fagan (1997) who found that resource depletion increased cost at an average annual rate of 7 percent onshore and 12 percent offshore from 1974 to 1994.

Table 2 shows how many years it takes to double the regional finding costs, for a given R&D level and if future annual increase in regional oil production is as in 2009. For the four regions with the highest depletion effects, i.e. Canada, Africa, Other Western Hemisphere and Europe, it takes fewest years before the costs are twice as high as in 2009. Likewise, the four regions which reach a doubling of the costs latest, are the regions with the smallest depletion effects. Even if the Middle East has the

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[12] The exception is Europe and FSU where depletion mitigated technological growth from around 1991 and 2001, respectively.

[13] Our annual rate of decline in finding costs in the USA (and other regions) due to technological progress over the 1985-1995 period was around 11 percent. This is somewhat higher than Forbes and Zampelli (2000), who found a rate of technological growth of 8,3 percent over the same period for the USA. However, they did not focus on costs but on drilling success rates.

smallest depletion effect, the cost is twice as high after 10 years, which is on the average. However, the cost increase for this region is from a generally low level.

**Table 2. Number of years to a doubling of the finding costs for different regions**

| Canada | Africa | Other Western Hemisphere | Europe | Middle East | Other Eastern Hemisphere | USA | Former Soviet Union |
|---|---|---|---|---|---|---|---|
| 7 | 7 | 8 | 9 | 10 | 10 | 12 | 13 |

We emphasize that the data for finding costs are from U.S. petroleum companies operating in different regions. To the extent that these companies do not reflect regional cost structures, we may falsely conclude on regional conditions. However, we have no indications that the costs level of these U.S. based companies should differ much from the cost level in the regions where they operate. Exceptions are probably the Middle East and the Former Soviet Union, where foreign companies may have less access to the low-cost reserves. In addition, in our estimation we assume that average finding costs for oil and gas reflect oil costs. We do not have any a priori indications how this assumption may affect our results.

We apply R&D expenses as a proxy for technological change. It is true that R&D gives rise to inventions and innovations. However, not all of these lead to the diffusion of successful technologies.[14] In addition, some innovations may have originated in other industries and therefore is not linked to the R&D expenses in the petroleum sector. Hence, expenditures on R&D may be a rough measure of the effect of technology in reducing finding costs. However, our measure is a more precise proxy for technological growth than a linear time trend that may embody various other effects than technological. We emphasize that with a linear time-trend instead of R&D expenses we find that the constant annual rate of technological growth was around 10 percent. This is not far from the average annual technological progress due to R&D activity which was around 9 percent over the whole period.

There is a risk that our highly aggregated macro-level data can obscure the effects of economic and policy variables on the pattern of E&D activities. However, focusing on micro-level data as single fields in one region also involves tradeoffs. In doing so one ignore broader factors which can be important in determining whether technological change has overcome depletion at the macro level.

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[14] We could not find data for patents in the petroleum sector over the whole period.

Can we say something about future development of costs in the oil sector? Except for cyclical changes in average finding costs that could come from changes in factor prices, regional finding costs *could* stay at the present level or even decline. This is dependent on that future R&D effort is successful in leading to cost-reducing technological growth that can outweigh the rate of depletion. Kemp and Kalim (2006) point out that to stimulate a reduction in costs and to enhance exploration efficiency a greater R&D effort is required than has been the case in recent years.

# 5. Conclusions

This study provides an empirical analysis of the extent to which ongoing technological change has offset the effect of ongoing depletion on the cost of finding and developing additional reserves of oil. From a Cobb-Douglas type of production function we derive regional functions of oil finding costs. We study the effects of depletion and technological change for eight global regions over the 1981-2009 period.

We apply cumulative production as a proxy for regional specific depletion and R&D expenses as an indication of the rate of technological advance over time. The cumulative total R&D expenses over all regions is an indicator of the level of technology, taking spillover effects between the oil companies into account.

For all our regions we find significant effects of both depletion and technological change on oil finding costs from 1981 to 2009, barring cyclical variations in finding costs that could come from changes in factor prices. For almost all regions technology more than mitigated depletion until around the mid-nineties. However, we find that depletion outweighed technological progress over the last decade.

Except for cyclical changes in finding costs that could come from higher factor prices, regional finding costs could stay at the present level or even decline in the future. Such a development is conditioned on that future R&D activity is successful in supporting cost-reducing technological growth.

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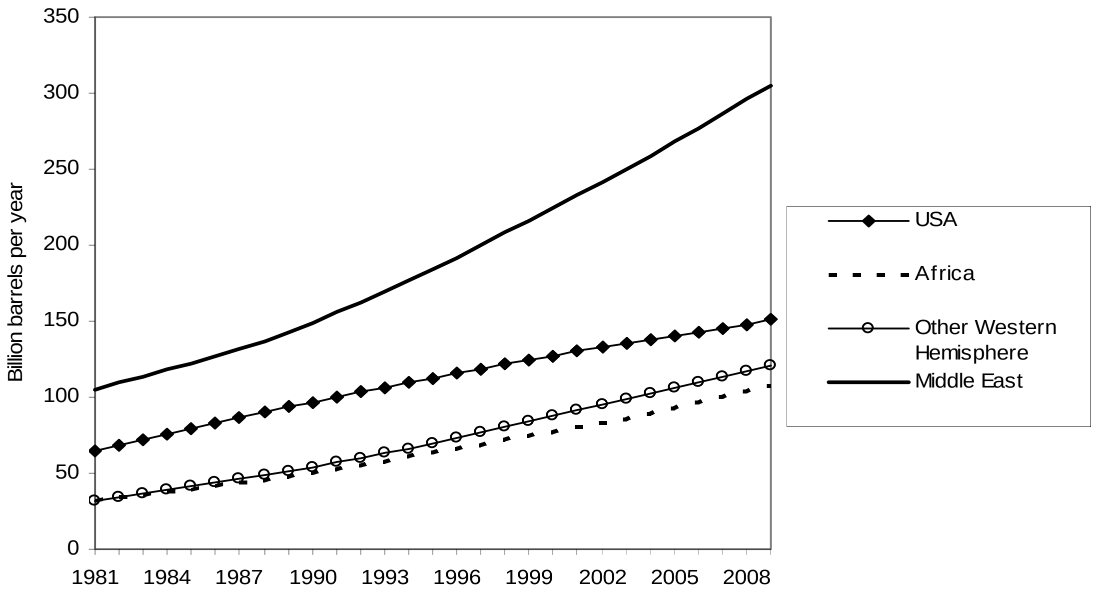
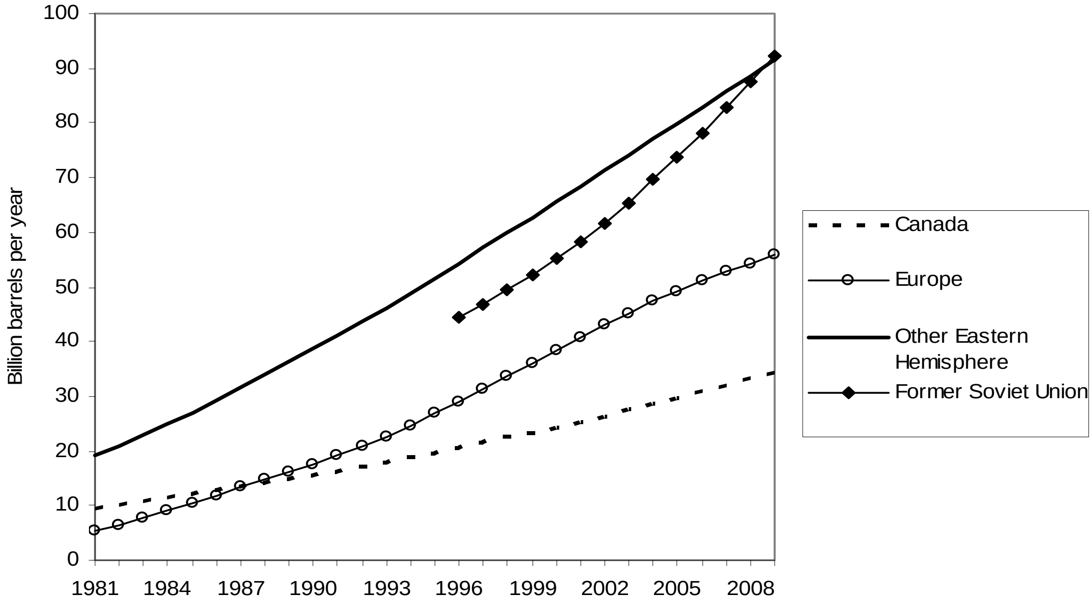
# Appendix

**Figure 1A. Regional cumulative output for USA, Africa, Other Western Hemisphere and Middle East. Billion barrels per year**



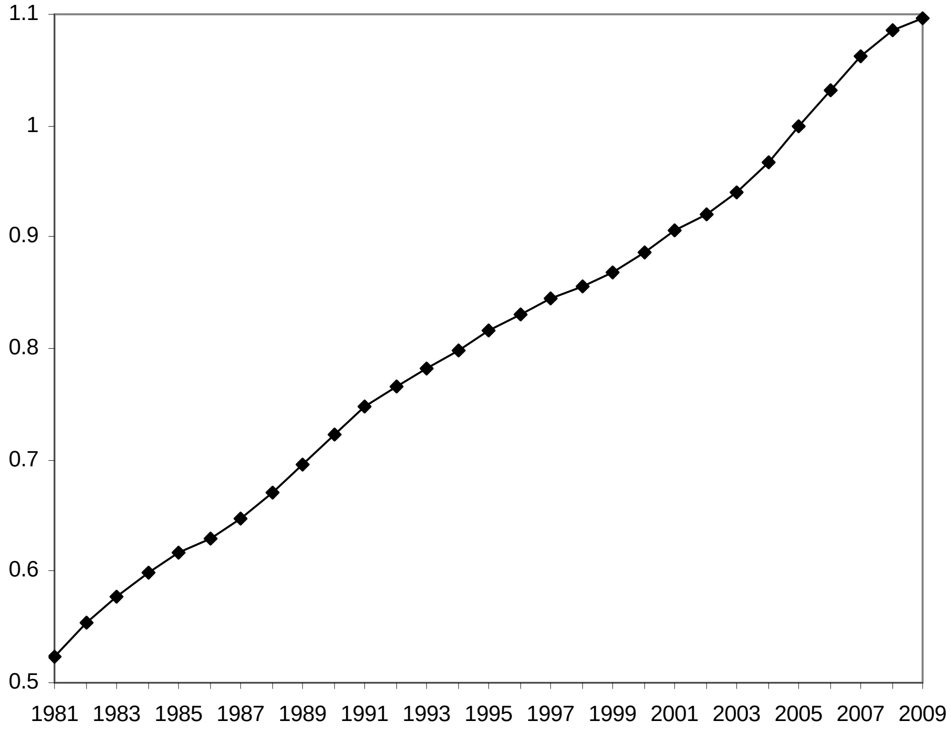

Source: EIA (2012a)

**Figure 2A. Regional cumulative output for Canada, Europe, Other Eastern Hemisphere and Former Soviet Union. Billion barrels per year**




Source: EIA (2012a)

**Figure 3A.  US GDP Price Deflator - 2005=1**




Source: Bureau of Economic Analysis (2012)

**B**

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