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Technology Learning and investment needs for upstream oil and the LNG chain

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1. Introduction

Off-shore oil production and gas transport in the form of Liquid Natural Gas (LNG) are two of the fastest growing sectors in the oil and gas markets. They are both capital intense and their growth will require substantial investments in the future (IEA/OECD 2003a). However, technologies in both sectors have showed remarkable progress over the last decades, improving performance and lowering costs (Cleveland and Kaufmann 1997, Standards and Poor 2001, Albertin et al.2002, Delaytermoz and Lecourtier 2001). Questions arise about future progress in cost and performance and how such *technology learning* will affect the amount of capital needed for investments and ultimately oil and gas prices.

Experience and learning curves (Wright 1936, Boston Consulting Group 1978) have proven to be useful tools to assess progress in technologies that are deployed in competitive markets (Abell and Hammond 1979, Argote and Epple 1990, IEA/OECD 2000, IEA/OECD 2003b). An experience curve analysis relies on historical analysis and benchmark values for technology learning as result of market deployment. The analysis focuses on strategic systemic parameters such as cost and performance without going into the specific developments in the technology leading to the reductions in cost and improvements in performance. Such a top-down view of technology learning is very useful in policy analysis (IEA/OECD 2000) but also for estimating capital needed in future investments.

This paper summarizes findings of reports on experience curve analysis for upstream oil (Wene 2003b) and for the LNG chain (Wene 2003a). The reports were written for the IEA World Energy Investments Outlook, WEIO (IEA/OECD 2003a). The purpose of the reports was to assess the effects of technology learning on the amount of capital needed for investments in the two sectors over the 30 years period 2001-2030. The analysis starts from the Reference Scenario used in WEIO for oil production and LNG transport in the 30 years period. Technology Learning Scenarios are then constructed based on historical analysis and benchmark values for the learning parameter in the experience curves for the different technologies.

The analysis raises several methodological issues, e.g., the interpretation of historical experience curves in view of price-cost cycles or fundamental technological changes and the generation of relevant Technology Learning Scenarios based on these interpretations. The upstream oil sector presents a special case because the technologies operate on an exhaustible resource base. The methodological issues are discussed in the following section. The results of the analysis of historical data are discussed in section 3 and the construction of Technology Learning Scenarios in section 4. Section 5 provides scenario results. The two reports provide a more detailed discussion of both analysis and results than can be made available here.

2. Methodology

2.1. Interpretation of historical experience curves

Experience curves are described by the following mathematical expression

Price at year t = $P_0 * X(t)^{-E}$

"P_0 " is a constant equal to the price at one unit of cumulative production or sales. "X(t)" is cumulative production or sales in year t. "E" is the (positive) experience parameter, which characterises the inclination of the curve. The *learning rate*, "LR" is the relative reduction in price after each doubling of cumulative production or sales. It is given by

$LR = 1 - 2^{-E}$

The literature on experience curves also uses the term *progress ratios*, PR = 1 – LR.

The experience curve is a semi-empirical phenomenon, that is, there is overwhelming empirical support for such a price-experience relationship from all fields of industrial activities, but there is yet no theoretical explanation for the shape of the curve. To avoid some common pitfalls in extrapolating historical curves for scenario analysis, three issues should be discussed (cf. IEA/OECD 2000, chapter 2 and Wene 2003a):

- *Benchmarking.* The measured learning rates should be compared to ratios measured for other (similar) technologies. Major differences could be due to price-cost cycles or to fundamental change in the technology during the measuring period and signals that care should be exercised in extrapolating the results. The same is true if the learning rates change abruptly in the period.
- *Price-Cost Cycle*. Prices can be observed in the markets, but cost data are usually very difficult to obtain. In equilibrium markets, we expect cost and prices to appear as two parallel lines in a log-log diagram, the ratio indicating profit margins in the industry. The work by the Boston Consulting Group (1968) indicates that there may be price-cost cycles where a period with a low learning rate may be followed by a short period with a very high learning rate. Such shakeouts in prices signal market changes, and apparent learning rates from such periods cannot be used for extrapolation.
- *Technology Structural Change.* A fundamental change in technology may appear as a strong sudden increase in learning rate for ***costs.*** One expects that the reduction in cost would show up also in prices, but without other evidence for fundamental technological change, it may be difficult to distinguish from market changes in the price-cost cycle. Additional proofs are required, for instance learning curves for technical properties such

as efficiency and bottom-up analysis of the technology. Technology structural changes can be handled in different ways in the experience curve formalism. In the analysis presented here, the cumulative production, X, is renormalized and set to zero at the time of the change.

For Benchmarking, there are two publications on the distribution of progress ratios and learning rates available in the literature (Dutton and Thomas, 1984 and McDonald and Schrattenholzer, 2001).

The distribution in Dutton and Thomas (1984) includes progress ratios from 108 cases in 22 field studies. All measurements are made inside firms and include manufacturing processes in industries such as electronics, machine tools, system components for electronic data processing, papermaking, aircraft, steel, apparel, and automobiles. Industry-level progress ratios are excluded. The average value and the most probable value for the progress ratio are both 82%, which corresponds to 18% learning rate.

McDonald and Schrattenholzer (2001) have compiled 42 learning rates of energy technologies that were either published or based on calculations by the authors. Contrary to Dutton and Thomas, the experience curves are measured on industrial level. The authors find two peaks in the distribution: one around learning rates of 18%, and one around learning rates of 2-6% (94-98% progress ratio). The first peak coincides well with the one found by Dutton and Thomas, a typical energy technology found in this peak is photovoltaic modules. Wind *turbines* are found in the second peak at 2-6% learning rates. However, it should be noted that Junginger et al. (2004) finds learning rates of 15-23% with an average of 19% for wind farms, that is for complete plants.

The interpretation of McDonald and Schrattenholzer's distribution proposed in this paper, is that new emerging technologies will be expected to move at a learning rate of about 18 percent, but technologies built on grafting old technologies will have a much lower overall learning rate. A technology with a learning rate for cost reductions of 18% will be referred to as a "Dutton-Thomas technology". Examples of technologies, which are grafted old technologies, are wind turbines, coal fired power plants with advanced thermodynamic cycles, and natural gas combined cycle. The grafts themselves may move at 18% learning rates, but the cost for the whole technology moves at a much lower rate.

Ideally, the analysis of historical data should make it possible for us to decide whether the technologies should be classified as "Dutton-Thomas" or "grafted". However, as will be seen, the analysis indicates strong influence of both market effects and technology change. Furthermore, for the LNG chain, the learning systems do not produce bulk products, such as PV-modules or wind turbines, but are geared up for customs designed projects, producing single ships or constructing large liquefaction plants. As expected, the statistical spread around the experience curve is large (compare for instance the case study on solar heating with the case studies on wind and PV in IEA/OECD (2000)). Technology Learning Scenarios will have to acknowledge these uncertainties and be constructed to encompass, or "bracket", plausible interpretations of historical data.

2.2 The effects of exhaustible inputs

The analysis of experience curves for oil exploration and development of reserves for crude production is complicated by the fact that the oil inputs to the learning system are exhaustible and may not be properly valued in the total input cost. This means that observed time series of cost have changing mix of resources and reserves and may be difficult to interpret in the technology learning framework. Figure 1 illustrates this argument. The basic cybernetic model of the experience curve (Wene,1999 and IEA/OECD 2000, p.27) assumes that all inputs can be consistently valued in one currency and added together to provide the total cost to produce the output. But figure 1 suggests that the inputs “Oil Resources” and “Reserves” are not properly monetized and not added to the “Monetized Inputs”, which are labour, capital, raw materials and energy.

In discussing Figure 1 it is important to remember that *experience* curves refer to ***all*** costs that are necessary to produce one unit of output from the learning system. *Learning* curves on the other hand refer to only one out of two or more inputs, e.g., labour or capital[1], to produce one unit of output. The Boston Consulting Group (1968) which introduced this important distinction observes that experience curves include “all of the cost elements which may have a trade-off against each other. This therefore means all costs of every kind required to deliver the product to the ultimate user, including the cost of intangibles which affect perceived value. There is no question that R&D, sales expenses, advertising, overhead, and everything else is included” (p.12). It is important to note that by looking at a learning curve we cannot tell whether improved performance relative to the specific input is due to more efficient use of this input in the learning system or due to the input being substituted for another input, e.g. capital for labour. Such a curve cannot be easily benchmarked against curves for other technologies, because it reflects changes in the environment outside the control of the feedback loop, for instance changes in relative prices of different inputs. A learning curve with a very high learning rate could therefore indicate that the learning system over the observed period was just increasing the share of uncontrolled inputs relative to the controlled input to produce a unit of output. To interpret the time series in the technology learning framework requires either that uncontrolled inputs have been constant or ways to correct for the change of such inputs.

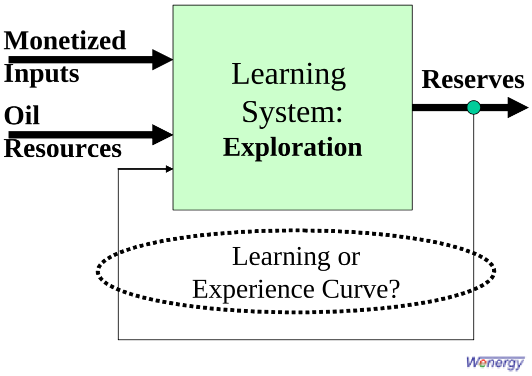

Figure 1A. Learning system for Exploration

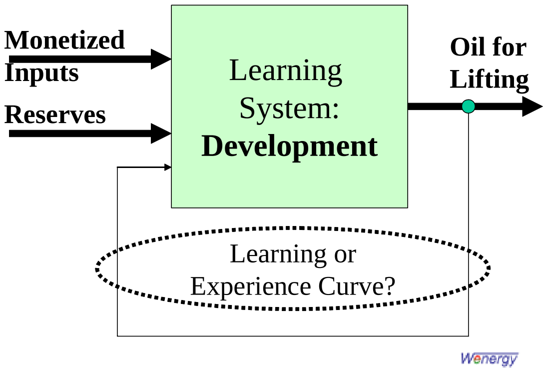

Figure 1B. Learning system for Development

In the terminology of the Boston Consulting Group, the crucial question for “Exploration” is thus whether a plot of reported exploration costs versus cumulative findings represents a learning curve or an experience curve for the exploration learning system. Figure 1A suggests that the observed cost-findings relation only represents a learning curve. That is, the curve reflects both the learning going on within the system and the fact that as a play is being

[1] The controlled input to which the learning curve refers can be a sum of several inputs measured in the same unit, e.g., “monetized inputs” as in figure 1. But, as long as the sum does not include all inputs the curve is in this paper called a learning curve.

exhausted the finds will be smaller and smaller which should drive up the cost per barrel. This means, that there is an uncontrolled trade off between monetized inputs and oil resources. To understand the technology learning that has taken place and make forecast for the future it would then be necessary to correct for the effect of exhaustion of resources.

However, considering the process leading up to reserves and proven reserves indicates that the interpretation according to figure 1A of the observed relation between exploration costs and cumulative findings as a learning curve is *not* correct. Oil resources are indeed given a price, e.g. in the North Sea through an auction process. Oil companies buy the right to make resources into reserves. The question is then if the mechanisms in place to value resources correctly reflect the effect of resources depletion on the need for other inputs to the learning system, i.e., labour, capital, raw materials and energy. For instance, does the outcome of an auction correctly reflect the expectations about the distribution of field sizes? The second question is: do quoted exploration costs include the cost for the right to prospect for oil? If the answers to both these questions are “Yes”, then the observed relation between exploration cost and cumulative findings through exploration represents an experience curve.

The argument put forward in this paper is that the oil industry is a mature and competitive industry which should be able to correctly value its assets, i.e., the answer to the two questions is Yes. Consequently, the observed relation between exploration cost and cumulative finding through exploration provides a good first approximation to an experience curve for exploration.

For the Development learning system, reserves are the input. Such reserves get a market valuation when they are sold between companies (“reserve acquisition”). However, these costs do not enter into the quoted development cost so we cannot construct an experience curve for Development. The questions are then how much the mix of reserves being developed has changed over the last two decades and how such change would affect the cost for development.

Wene (2003b) observes that during the period 1980-2000, the ratio for onshore/offshore production in OPEC was almost constant, while outside of OPEC most investments went into development of offshore reserves. He concludes that available time series provide a learning curve for development, but it is possible to assess at least qualitatively the influence of uncontrolled inputs. Changing mix of developed reserves can influence the learning rate in two ways:

- *Regional differences*. Specific costs differ considerably between regions. E.g., oil price turbulence in the 80s may have made oil companies change their development portfolios reducing investments in more expensive regions. This increases the observed learning rate, but does not reflect improved technology learning. Conversely, specific cost may be reduced through learning and thus open up new regions which earlier were considered too expensive. This effect reduces the observed learning rate, thus making technology learning appear less effective.
- *Field size*. Developing starts with the larger fields, however, as costs are reduced through learning smaller fields become cost-efficient. Real technology progress is made, but its full impact is not reflected in the observed average development costs.

Further research would make it possible to estimate quantitatively the influence from the two factors. For this exercise, the influence from the two factors is considered in setting up and evaluating the Technology Learning Scenarios.

3. Experience Curve Analysis of Data Time Series

3.1 Oil Exploration and Development

Figure 2 shows the results of an experience curve analysis of cost for finding oil in the period 1985-1990 for the 7 major oil companies. The two curves are constructed from the same costs but with different entry points, that is with different assumptions on when accumulation of relevant experience started. The steep curve starts counting cumulative additions from 1968, i.e. X(1968)=0, and the flatter curve assumes X(1989)=0.

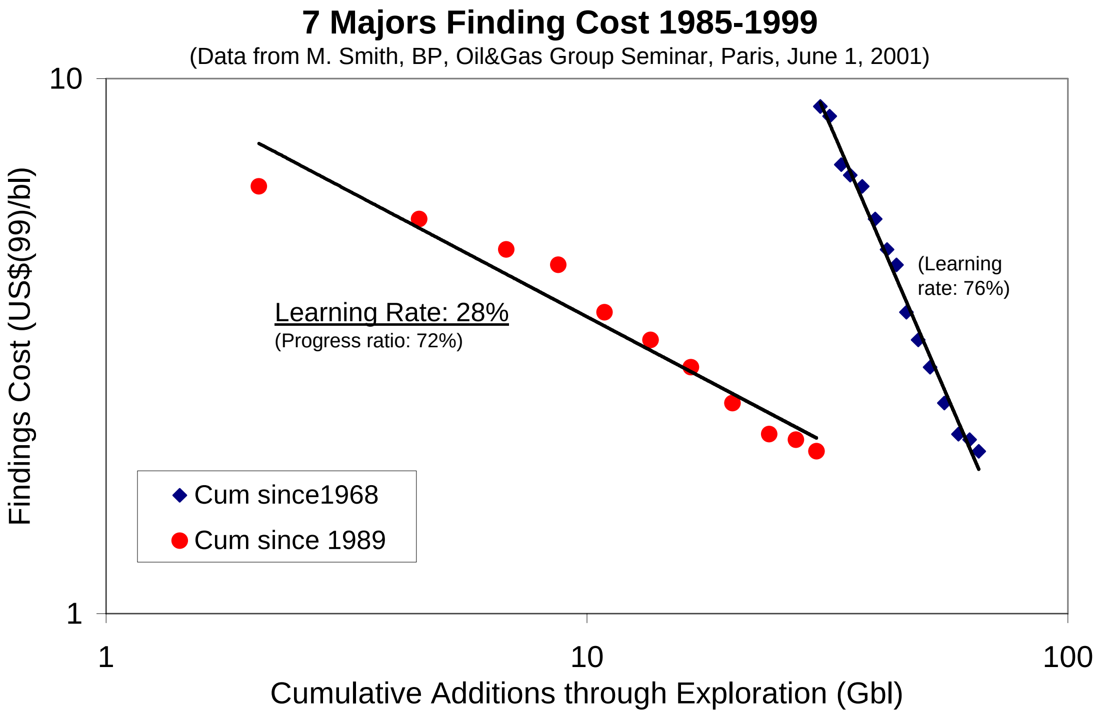

Figure 2. Experience Curve analysis of oil exploration. Data are from Smith (2001)[2].

The steep curve with X(1968)=0 shows an apparent learning rate of 76% which is completely outside any of the benchmark distributions discussed in section 2.1 above. It can be noted that en earlier entry point would further increase the learning rate[3]. Obviously, learning rates measured with entry points from 1968 or earlier have no prognostic values. The question is how we should interpret the steep reduction in exploration costs in the period 1985-1990. Is it a result of market shakeout or is it a result of a fundamental technology change?

Wene (2003b) argues that the major part of the observed cost reductions are the results of a technology structural change (TSC), and that the analysis should use X(1989)=0 placing the

[2] Smith's data are treated as *exploration* cost (i.e., excluding revisions and Enhanced Oil Recovery)
[3] E.g., setting X(1860)=0 would make the learning rate 1985-1990 equal to 83%!

start of the new technology regime at 1989. This provides a learning rate for exploration cost of 28%.

There are two independent indicators supporting the view of a TSC for exploration around 1990. One indicator is the introduction of 3D seismic technologies (Albertin et al. 2002) and the other indicator are the learning curves observed for wildcat performance[4]. The use of 3D seismic technology for new wildcats took off around 1990 and the area covered by this imaging technology grew from five thousand to over one million square kilometres between 1991 and 2000 (Wene 2003b). Figure 3 shows the performance of the wildcat learning system in the period 1947-2001. Up until 1968 the ratio of wildcats per successful wildcat was constant around 10. New technology introduced around 1968 started learning and an analysis with X(1968)=0 shows that the learning rate for the period 1968-1985 is 17%. Introducing 3D seismic technology started a new round of learning and setting X(1989)=0 provides a learning rate of 23% for the period 1989-2001 (Wene 2003b).

Analysis of exploration cost data from TotalFinaElf and Delaytermoz and Lecourtier (2001) shows learning rate of 26% for the period 1990-1999, confirming the results from the data for the 7 majors (Wene 2003b). In summary, the historical data are consistent with a technology structural change for oil exploration in 1989 resulting in learning rates as for a Dutton-Thomas technology or better.

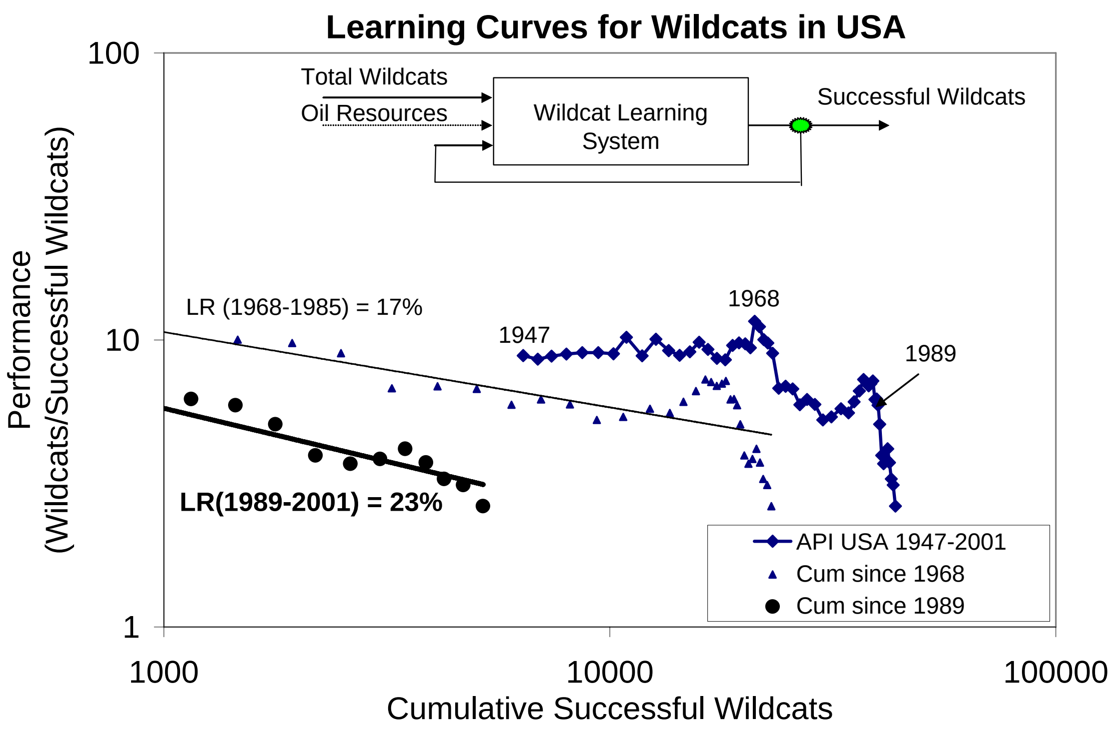

Figure 3. Performance for the US Wildcat learning system. Data from API (2002)

As for exploration, Communication and Information Technology (CIT) has enabled considerable technology change for *development of oil reserves*. Horizontal, multilateral and deviated wells with logging and measuring when drilling (LWD, MWD) are parts in a large

[4] A wildcat is an exploratory borehole drilled in an area that has not produced commercial amounts of oil before the drilling.

cluster of technologies with a large CIT component. As for exploring technologies, we can ask if the change has been so thorough that we can analyse learning and experience curves assuming a technology structural change in the second half of the 80s. And if so, did the change produce a Dutton-Thomas or a grafted technology?

Figure 4 shows the analysis of development costs for the seven majors 1985-1999. As pointed out in section 2.2., what is observed is a learning curve rather than an experience curve, although the learning rate is expected to be indicative for technology learning. Furthermore, because of lack of data, cumulative oil production is used as proxy for cumulative investments in oil reserve development.[5]

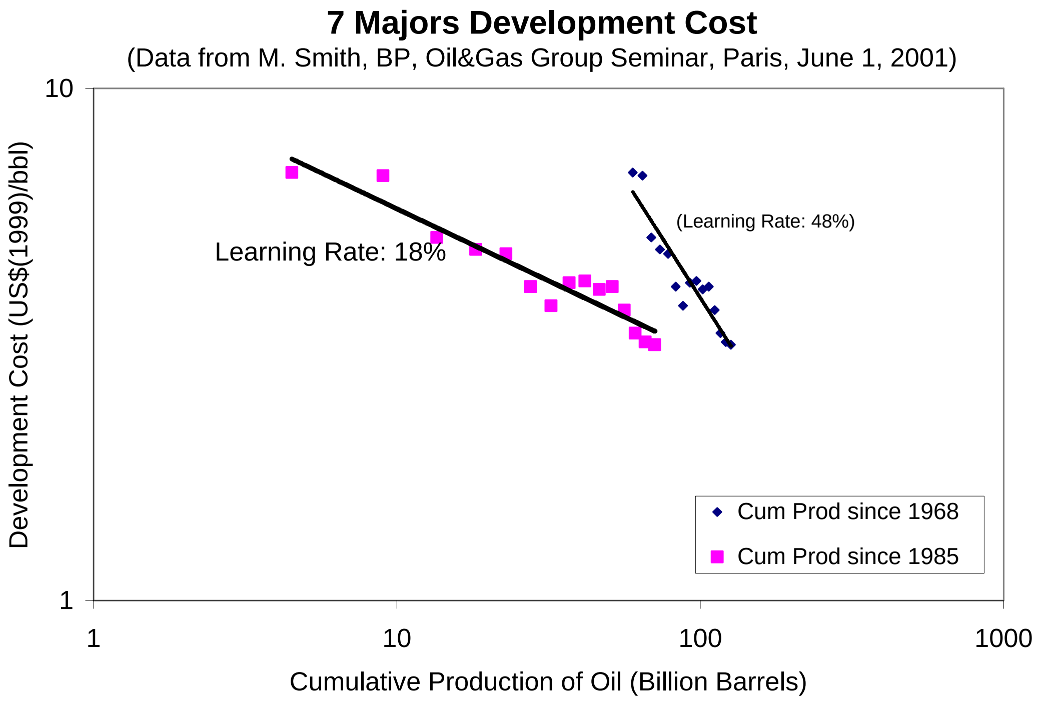

Figure 4. Majors learning curve for development. Note that the diagram only shows capital expenditure for production. Data from Smith (2001).

The analysis of the development cost is similar to the analysis for exploration. To initiate the analysis, the reported development costs were plotted against cumulative production from the seven majors since 1968. This gives a learning rate of 48% indicative of a market shakeout or a technology structural change. In the second step, the x-axis is renormalized to show cumulative production since 1985 following the indication of a possible technology change at this time from the analysis of development wells (Wene 2003b). The observed learning rate is 18%, i.e., the typical learning rate of a Dutton-Thomas technology. However, the interpretation of the learning curve poses several problems:

[5] The correct explanation variable ("x-axis") should be cumulative additions to production capacity given, e.g., in barrels/day. This information is not available, and cumulative production is used instead assuming that each barrel produced requires development to make one additional barrel available for lifting. This is not correct on an annual basis, but in a steady state it would probably be correct over the fifteen year period considered. However, the period has also seen an increase in bopd per barrel in the ground indicating that physical capacity for production has increased faster than production. This means that the choice of explaining variable may overestimate the learning rate. (bopd = barrel of oil per day)

- So far the indications of a technology structural change around 1985 is weak and should be corroborated with further analysis of technical performance
- A competitive interpretation of the curve is market shakeout. To rule out this possibility a longer time series is necessary
- The choice of explaining variable ("x-axis") may overestimate the observed learning rate.
- Influence of changes in the mix of developed reserves as discussed above in section 2.2.

It should be pointed out that we are here only looking at capital expenditure for production. The data from Smith (2001) and from Delaytermoz and Lecoutrier (2001) show that the reduction in operating costs are considerably stronger.

In conclusion, we find that the observed learning rate is consistent with a Dutton-Thomas technology. However, the empirical results are considerably less decisive than for Exploration. The analysis presently leaves open several questions about the starting point for cumulative production, whether observed development costs indicate market shakeout after 1985 or technology structural change, and the use of cumulative production as explaining variable in view of the present trend toward faster recycling of capital for development.

3.2. The LNG chain

The LNG chain contains three links: liquefaction plants, LNG tankers and regasification plants. Figures 5 and 6 provide experience curve analysis of time series for liquefaction plants and LNG tankers. In both cases the learning rates are very high, although they are still compatible with the benchmark distributions. However, there are indications that there were strong changes in markets or technologies in the 90s, and care should be exercised when extrapolating these learning rates. The alternative analysis in figure 5 indicates fairly normal cost reductions for liquefaction plants until1988 followed by a sharp reduction in the 90s. The curve for LNG tankers fits well to the data points, but covers only the period from 1991 to 2001. There are scant data from before 1991 that indicate a similar behaviour as for liquefaction plants (Wene 2003a). There are three explanations for the observed high learning rates, all warning against relying too much on these rates for investments forecasting:

- *Shakeout.* This means that market was too elevated before 1988. Against this argues the fairly normal behaviour for liquefaction plants until 1988. However, there may be other market factors, such as increasing reliance on cheaper, domestic labour which then could be interpreted as learning in form of spill-over and technology transfer. For LNG tankers one could easily envisage market effects in the highly competitive and global shipbuilding industry scrambling to position themselves in a very promising prospective market (including state subsidies).
- *Technology Structural Change*. Setting the cumulative installed capacity for liquefaction plants to zero in 1987 gives a learning rate of 28% (PR=72%), which still is on the high side but not unreasonable. For LNG tankers, the literature indicates considerable technological progress in the 90s and that there are several technologies competing for implementation in future tankers. Setting X(1991)=0 gives a learning rate of 19 %.
- *The Output from the Learning System is Systematically Changing*. This would mean that the product "Liquefaction Plant" is not the same in 1990 as in 1980. Example would be that the projects turn more and more to expanding capacity on sites where the infrastructure is already developed, which would reduce cost without learning.

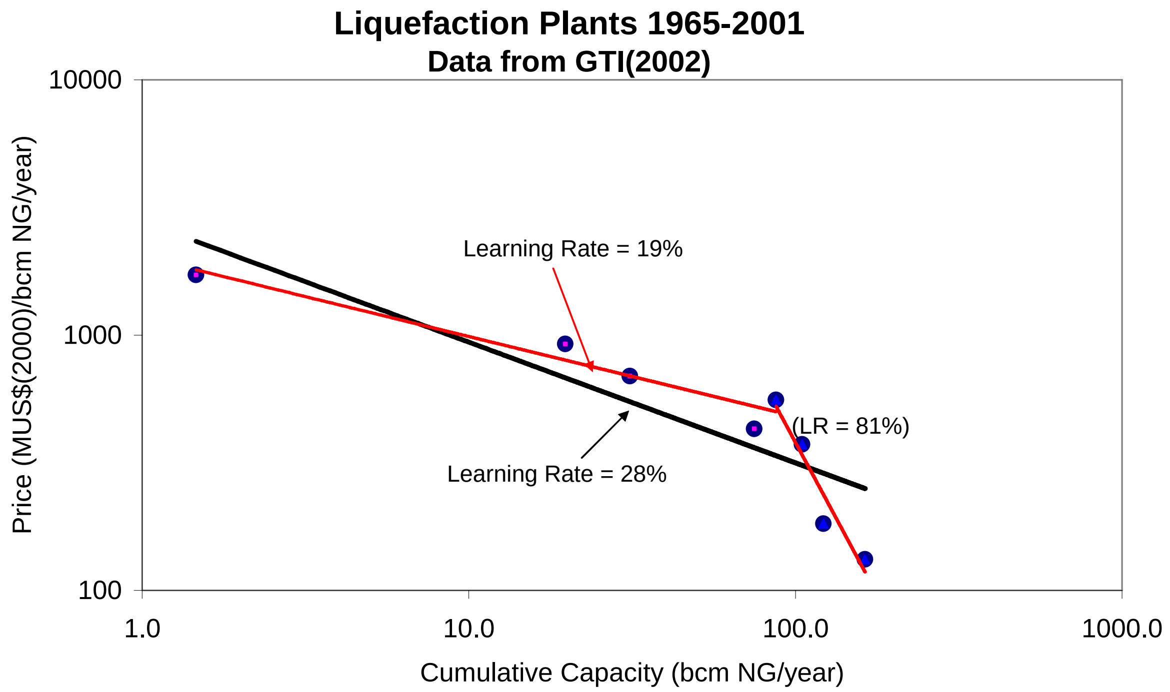

Figure 5. Experience Curve analysis for Liquefaction Plants. Data from GTI(2002)

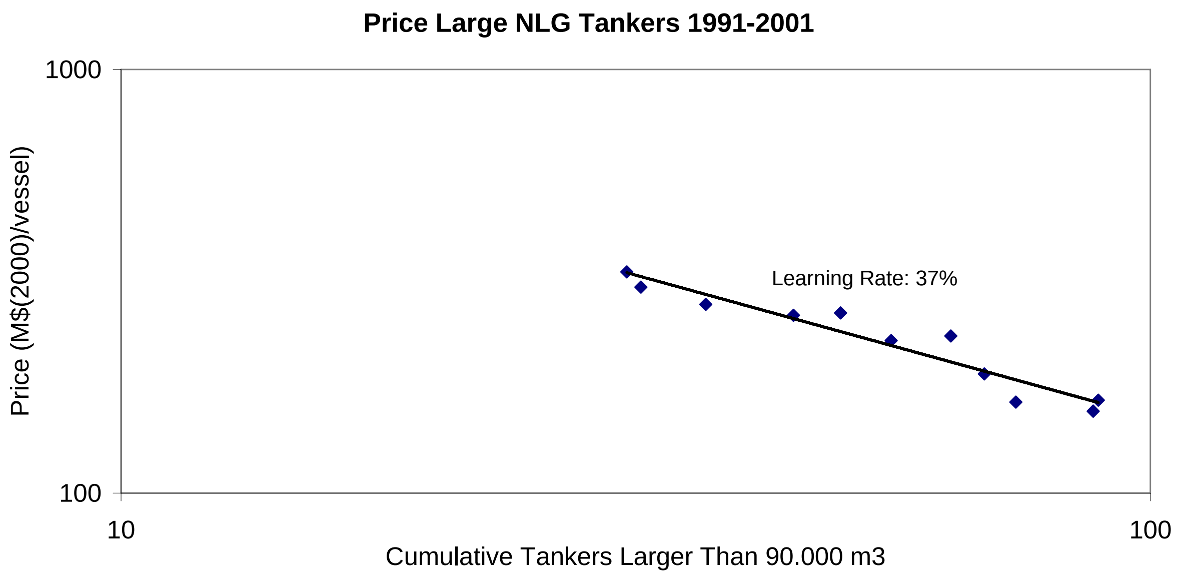

Figure 6. Experience Curve analysis for the LNG tanker fleet. Data from GTI(2002)

4. Technology Scenarios

4.1. Oil Exploration and Development

The basic assumption for *exploration* technology is that it can be treated as a Dutton-Thomas technology with an entry point in 1989, meaning that cumulative findings should be counted from that year. However, the historical analysis in the previous section indicates that a learning rate of 18% for the period 2000-2030 is a conservative choice. To “bracket” reasonable outcomes of technology learning a technology optimist scenario is constructed with a learning rate of 28% for exploration technologies. Although the analysis strongly points to high learning rates, we have not completely ruled out that other factors than technology have reduced exploration costs, e.g., oil market prices or improper valuation of the probability for large fields. The basic assumption is therefore balanced by a more pessimistic alternative assuming that the underlying and sustainable real cost decrease will follow an experience curve with a learning rate of 5% corresponding to a grafted technology. For comparison we also calculate capital needed for 0% learning rate.

For oil field *development*, our analysis yields a learning curve. The analysis in 3.1 indicates that the cost reductions are as for a Dutton-Thomas technology. However, following the discussion in 2.2., one cannot presently conclude whether a learning rate of 18% underestimates or overestimates the potential for cost reductions. Furthermore, the indications for technology structural change are weaker than for exploration. To this author, scenarios with grafted technology and Dutton-Thomas technology therefore appear equally probable. The pessimist may also argue that cost increases due to exhausting the resource base will cancel out cost reductions due to technology learning. A scenario with no visible effect of learning, that is an apparent learning rate of 0%, therefore represents a possible but less probable outcome for oil field development.

The calculation of investments in is made by a simple model described in Wene (2003b). Based on the Reference Scenario for oil supply in IEA/OECD (2003a), the model calculates physical investments in exploration and development for seven different sources of oil: OPEC-Middle East, OPEC-Rest, and Non-OPEC On-shore, Off-shore Shallow, Off-shore Deep Water, Off-shore Ultra-Deep Water, and Unconventional.[6] There are two basic technologies one for Exploration and one for Development. The basic technology is assumed similar for all the conventional sources and the learning is global. This means that deployment for Exploration and Development, respectively, is summed and a cumulative global deployment is calculated. The specific costs for the basic technology differ for the six sources, reflecting regional differences. But the yearly relative cost reductions are the same for all sources and based on the cumulative global deployment.

For offshore activities, investment costs are split into two components: one referring to the basic technology with global learning and one specific to the offshore source with independent and local learning. Independent learning means that the cost reductions for the offshore component are based only on the cumulative deployment of this component. For shallow-water sources the added cost is small, but ultra-deep water technologies are expected to initially carry a large extra cost. In this paper we assume the same learning rates for all

[6] The terminology follows the distinctions made in the industry:
shallow water: production in water depths until 500 m
deep water: production in water depths between 500 m and 1500 m
ultra-deep water: production in water depths larger than 1500 m

technologies within a scenario, but one can imagine scenario variations with different learning rates for the add-on technologies. Notice, that the same learning rate does *not* mean that all technologies reduce their cost at the same rate! The component specific to ultra-deep water technology will have a very small entry value in 2000 for the cumulative implementation of this technology, which means that cost reductions will come very quickly as this technology is being deployed.

The results presented in section 5 have been obtained assuming the following set of investment costs in the year 2001 (referred to in the figures as TED4FED costs). All costs are in US$(2000).

	Exploration		**Development**	
	Basic Global learning (US$/bl)	Add-on Learning by source (US$/bl)	Basic Global learning (US$/bl)	Add-on Learning by source (US$/bl)
Source				
OPEC-ME	0.15		0.84	
OPEC-Rest	1.30		1.75	
Onshore Non-OPEC	1.56		1.75	
Offshore Shallow	1.70	0	2.40	0
Offshore Deep	1.70	0.5	2.40	1.30
Offshore Ultradeep	1.70	1.0	2.40	2.60

4.2. The LNG Chain

Three experience curve scenarios were generated for the links in the LNG chain assuming learning rates of 18% (Dutton-Thomas technologies), 5% (grafted technologies) and one based on the measured learning rates (technology optimist). For the WEIO, literature studies had produced estimates of capital needs for investments based on experts views on future cost reduction (Cozzi 2003). In the following we refer to these estimates as a Delphi scenario. The Delphi scenario provides an opportunity to compare results from an experience curve analysis with estimates from independent professionals in the field.

For all scenarios the need for physical investments in liquefaction plants, LNG tankers and regasification plants were calculated from the Reference Scenario in IEA/OECD (2003a).

5. Results

5.1. Oil Exploration and Development

Figure 7 show annual investments in oil *exploration* for the period 2001-2030 assuming that cost reductions follow a learning rate of 18%. Total investments are of about 10 billion US$ in 2001 growing to over 15 billion US$ in 2010. Technology learning, especially in deep and ultradeep offshore exploration then slightly reduces the capital needed in spite of increasing exploration to around 14 billion US$ in 2030. Andersen (2001) gives capital expenditures of 18 billion US$ for oil *and* gas exploration in 2000 for the 155 oil&gas companies in their survey leading to the discovery of 5.5 billion barrels of oil and 6.2 billion barrels of oil equivalent of natural gas. The allocation of cost between oil and gas discoveries is not straightforward, but our model results for 2001 are consistent with these data.

The strong increase in annual cost until 2010 mainly reflects the expansion in the offshore industry. Between 2000 and 2010, OPEC provides over 60% of the *increase* in demand for conventional oil while offshore oil outside of OPEC provides 25%. The cost for exploration in OPEC is much smaller than for offshore fields and the increase of offshore activities has therefore a much larger impact on total investments. It should also be pointed out that there is a strong reduction in R/P for all onshore and shallow-water sources in the WEIO oil production scenario which is the base for our technology learning scenarios. These reduction cushions the cost increase in all the technology scenarios.

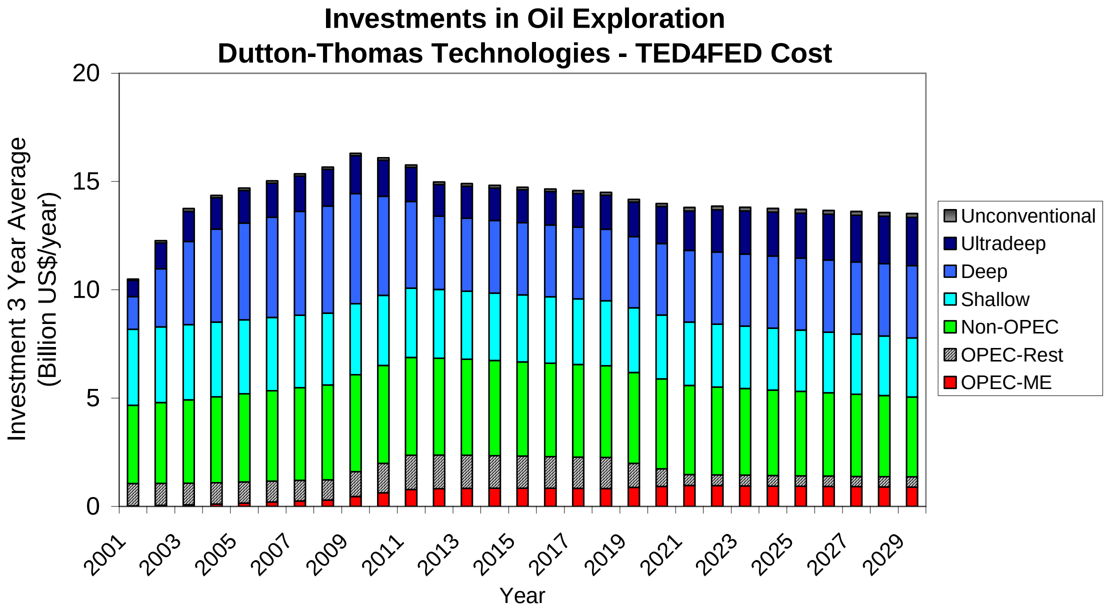

Figure 7. Annual investments in Exploration assuming 18% learning rate for exploration costs. Costs are in US$(2000).

Figure 8 compares the total capital expenditures for Exploration 2001-2030 for all technology learning scenarios. Assuming historical rates for learning reduce investments by 35% relative to the case with no visible effect.

Our analysis thus places the 30 years investments for exploration of conventional oil resources in the bracket of 350 to 580 billion US$(2000) with a most probable value around 430 billion US$(2000).

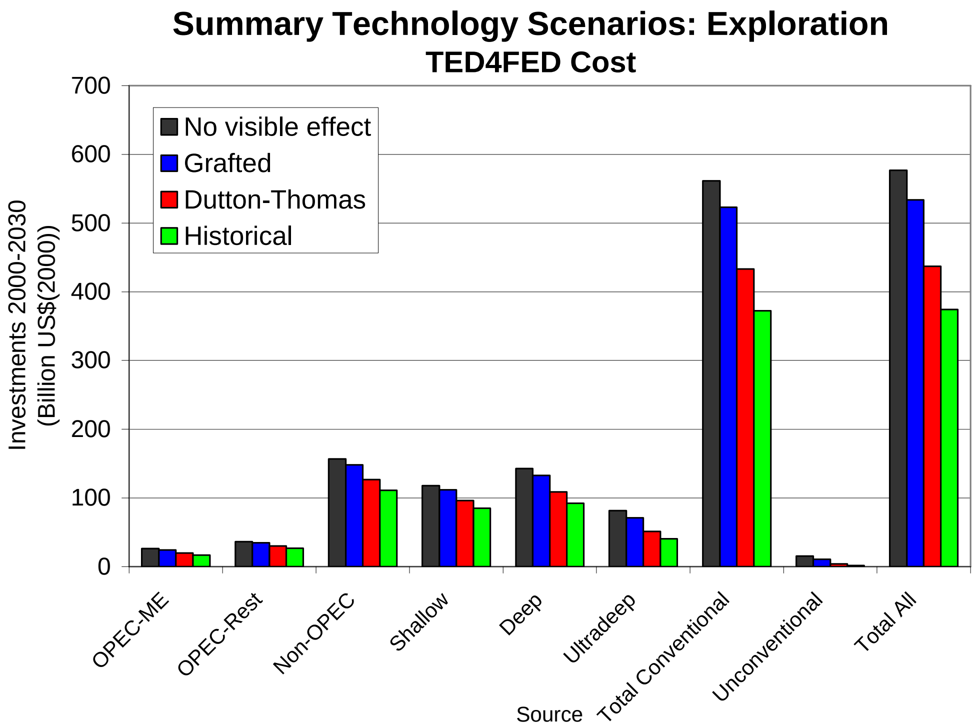

Figure 8. Investments in Exploration 2001-2030 in the technology learning scenarios.

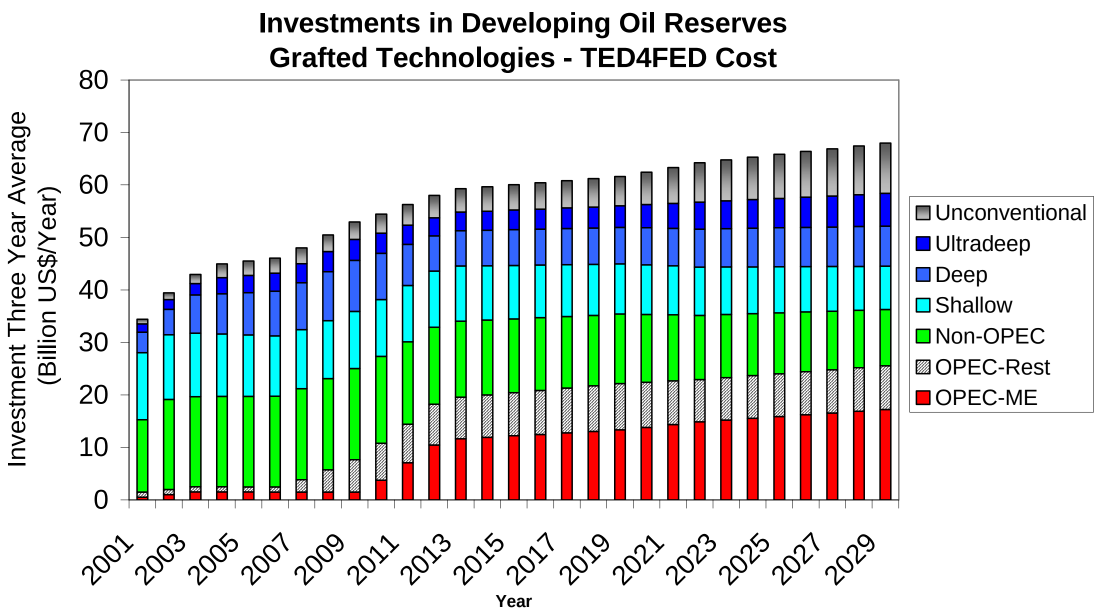

Figure 9. Annual investments in Development assuming 5% learning rate. Costs are in US$(2000).

Figure 9 shows annual investments for development of oil fields in the period 2001-2030 assuming learning rates similar to grafted technologies. Annual investments for conventional resources increase from about 35 US$/year to 50 US$/year in 2030. Three factors explain this increase: the increase in consumption from 75 to 120 million bbl/day, the expansion of the deep water production until 2010, and finally the need for new investments in capacity in OPEC-ME. Following the analysis in EIA(1996), the model calculations assume that the yields of the developed fields in the Middle East are fairly low and that these yields can be increased by fairly small investments. By 2010, this slack in yield has been used up and full cost reinvestments are necessary.

The effect of technology learning is not as strong as for Exploration. With a 5% learning rate the need for investments are reduced by 10% at the end of the period compared with the scenario of no visible effects of learning ("LR=0"). In the Dutton-Thomas scenario, annual investments for conventional oil sources increase to 45 billion US$ in 2015 and are then slightly reduced until 2030.

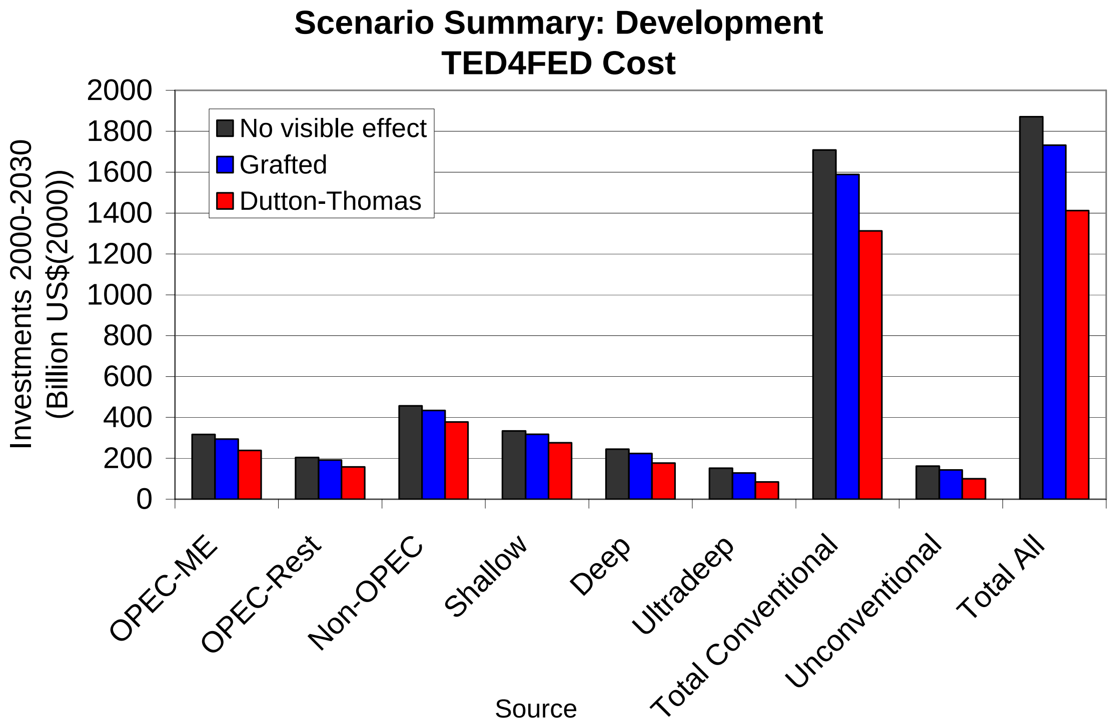

Figure 10. Investments in Development 2001-2030 in the technology scenarios.

Figure 10 compares the total investments over the 30 years period 2001-2030. Dutton-Thomas scenarios reduce the total investments by 20% and 25% relative to investments in a scenario with No Visible Effect of technology learning. Notice that investments in *developing* shallow water fields are larger than for deep water fields, but investments in *exploration* in Figure 8 are larger for the deep water fields. The development of R/P ratio explains this difference. Lowering the initial large 2001 R/P values for shallow water fields makes it possible to produce more from the shallow fields than what is discovered during the period studied. For the expanding deep water production, more has to be discovered than what is produced in the period in order to hold an R/P ratio of about 8. For production, we have not assumed any such "slack" in the yield from shallow water fields and the costs here reflects more closely the total production.

The analysis places the 30 years investments for development of conventional oil resources in the bracket of 1300 to 1700 billion US$(2000).

5.2. The LNG Chain

Figure 11 compares the total investments in the LNG chain obtained in the technology learning scenarios. An interesting result from this exercise is that the results from the Dutton-Thomas scenario and the Delphi scenario are very close to each other. It should be emphasised that physical investments are the same in the two scenarios, but the cost estimates are made independently of each other. The Dutton-Thomas scenario represents a top-down approach and uses a benchmark value for the learning rate corresponding to an average value found in two different distributions of historical measurements of a wide range of technologies and processes. The Delphi scenario is a bottom-up approach and represents future cost estimates from experts for three specific technologies. The concordant result lends credibility to the estimates.

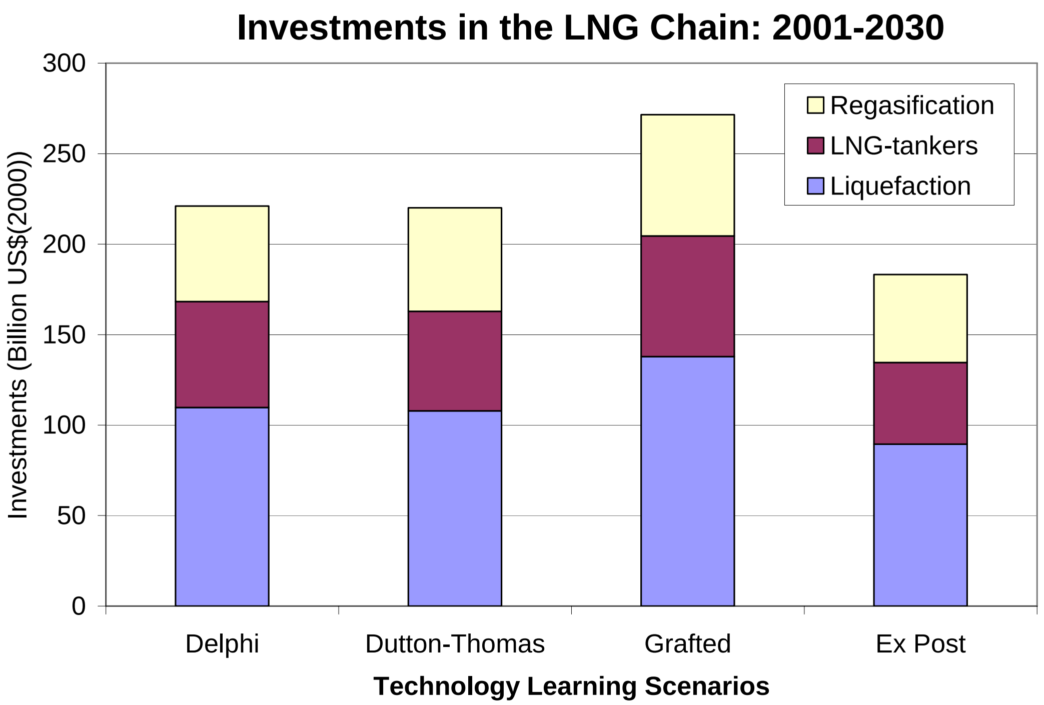

Figure 11. Summary of results for the LNG chain. The “Ex Post” estimates are made using the learning rates from the historical analysis in section 3.2.

6. Conclusion

Considering the effects of technology learning, the Reference Scenario used in WEIO requires total investments 1700 and 2300 billion US$(2000) for conventional oil production in the period 2001-2030. For the LNG chain the analysis leads to total investments of 220 billion US$(2000) with the interval of 180-270 billion US$(2000) capturing the difference between the technology optimist and the technology pessimist.

The analysis emphasises the need to critically evaluate and interpret historical experience curves, especially if these rely on data over a short time period and will be used to estimate future reductions in cost or price. Learning rates from analysis of historical time series should be compared with benchmark values and checked for effects from price-cost cycles and fundamental changes in technology.

One way of handling technology changes is to renormalize the explanatory variable, i.e., setting cumulative investments equal to zero at the time of the change. This technique was used to represent technology structural changes for oil exploration and development. Other representations are possible, e.g., stepwise reduction in cost without renormalisation. More studies of historical time series are needed to find the proper representation of technology structural change in the experience curve methodology.

The learning curve analysis of oil field development raises the question about experience curve methodology to study exploitation of natural resources. Very large fields have acted as niche market for offshore technologies in shallow waters and act as niche markets for technologies in deep and ultradeep waters. The new and initially expensive technologies can be used for these large fields where the cost per barrel can still be carried by the market. As the companies learn to bring down the cost for deployment, smaller and smaller fields can be opened up, technology learning being the prerequisite for continuing exploitation. The niche market approach will help develop an experience curve methodology to investigate exploitation of exhaustible resources, but requires more studies of company behaviour.

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