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Investments in the Mid-stream LNG Chain and Technology Learning

1. Background

The purpose of this Memo is to use experience curve methodology to assess the effect of technology learning on estimates of investments for the mid-stream Liquid Natural Gas (LNG) chain over the period 2001-2030. For the purpose of the analysis the mid-stream LNG chain is defined in Figure 1. The chain has three links: Liquefaction Plants, LNG Tanker Fleet and Regasification Plants. Learning is assumed to take place independently in three different systems: constructing the two types of plants and the LNG tankers.

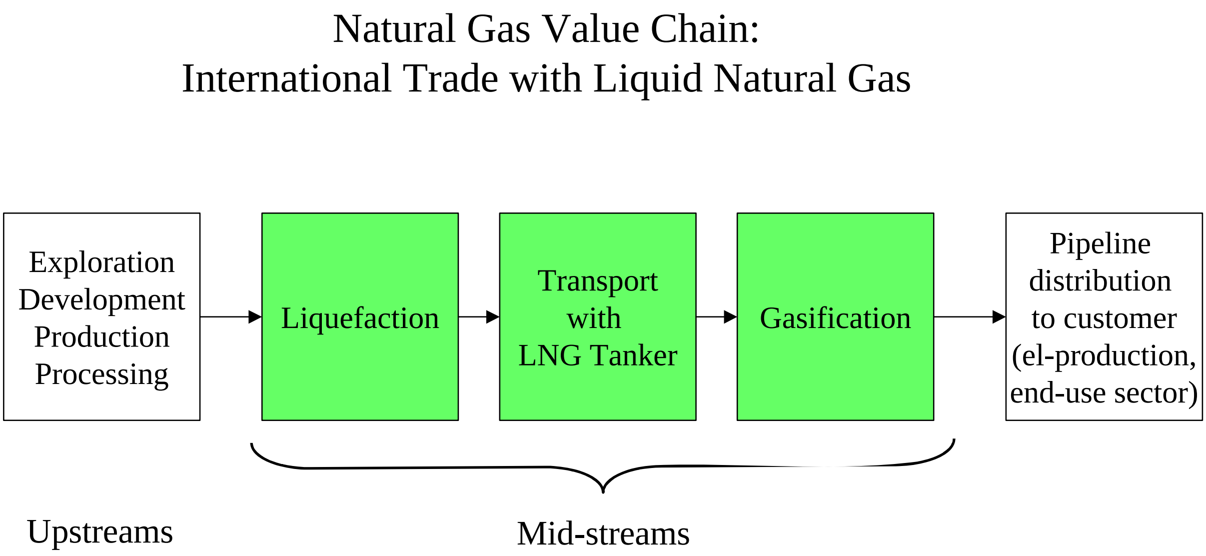

Figure 1. Gas value chain with LNG

The need for investments in physical capacity is taken from the Reference Scenario in WEO2002 (Laura Cozzi, 2003). Possible developments of investment prices during a 30-year period are then estimated with experience curve methodology built on historical analysis and benchmark progress ratios. Several different scenarios for technology learning are developed and it is argued that they together bracket reasonable continuous technology progress.

The experience curve methodology is discussed in more detail in the next session and the methodology is then applied to the three links in the LNG chain in section 3. Section 4 sums up the scenario results.

2. Methodology

Figure 2 depicts the methodology used.

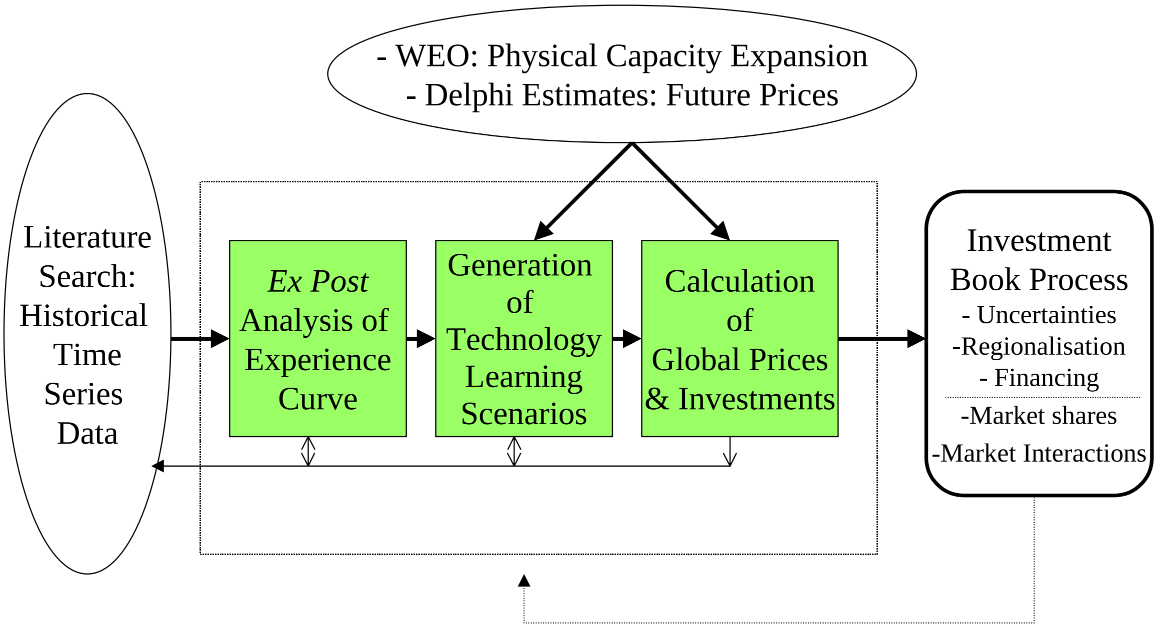

Figure 2. Experience Curve Methodology

Historical time series data on prices and capacity are obtained from the literature search made by Laura Cozzi. Delphi estimates of future prices are from the data collection and assessments already made by her, and are when possible taken from the literature search. The expression "Delphi estimates" indicates that the provided future prices in this stage of the work are treated as if obtained in a Delphi process. Ideally, they should represent present expectations of key representatives in the industry, whether grounded in detailed bottom-up analysis, or just plain intuition. It is important to confront such estimates with those obtained through experience curve analysis.

The major input from this exercise to the Investment book process is providing estimates on the possible effects of technology learning: "uncertainties in technology progress". Using a researched methodology to establish these estimates contributes to validating and benchmarking the overall results. However, the analysis could also provide input to discussions on regional distribution of technologies and their financing ("Is learning global or regional?", "Who will finance learning investments?") and, further down the road, when revisiting assessments of market shares and interactions ("Will learning substantially change the competition between different technologies and technology chains?").

The analysis reported here proceeded in three steps: Ex Post analysis of experience curves, Generation of technology learning scenarios and Calculation of global prices and investments.

2.1. Ex Post Analysis of Experience Curves

Analysis of historical data provides insight into the performance of the learning system, i.e., the manufacturer providing the equipment. How is this performance in relation to learning systems providing similar types of equipment (benchmarking)? Do prices reflect costs (price-cost cycle)? Have there been fundamental technical changes in the period (technology structural change)?

For benchmarking two sets of measurements of experience curves are available in the literature. Dutton and Thomas(1984) in Figure 3, shows the distribution in progress ratios from 108 cases in 22 field studies. The studies estimated the behaviour of cost with cumulative volume in 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.

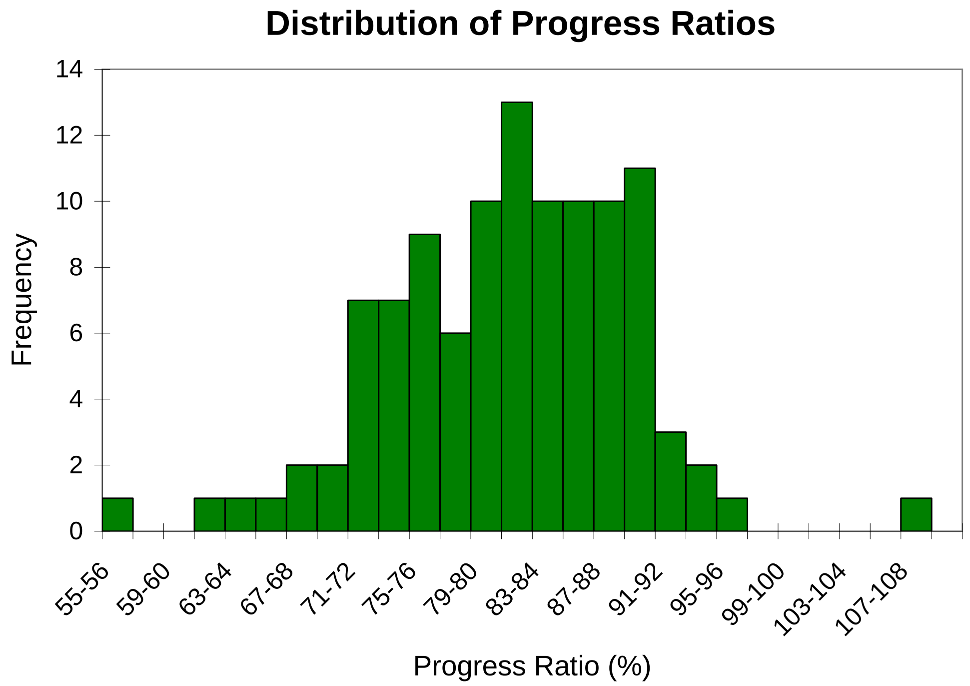

Figure 3. Progress ratios measured for 108 cases (Dutton and Thomas 1984)

McDonald and Schrattenholzer (2001) have compiled 42 learning rates of energy technologies that were either published or based on calculations by the authors. Their findings are summarised in Figure 4. Contrary to Dutton and Thomas, the experience curves are measured on industrial level. The authors find two peaks in the distribution one around a learning rates of 18%, corresponding to progress ratio of 82%, and one around a learning rate 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 the emblematic technology in the second peak at 2-6% learning rates.

My interpretation of McDonald and Schrattenholzer’s distribution is that we should expect new emerging technologies 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. Examples of technologies, which are grafted on old technologies, are wind turbines, coal fired power plants with advanced thermodynamic cycles, and natural gas combined cycle. Grafts may move at 18% learning rates, but the cost for the whole technology moves at a much lower rate. The question in our case is of course whether the three technologies we are looking at are really new or grafted ones.

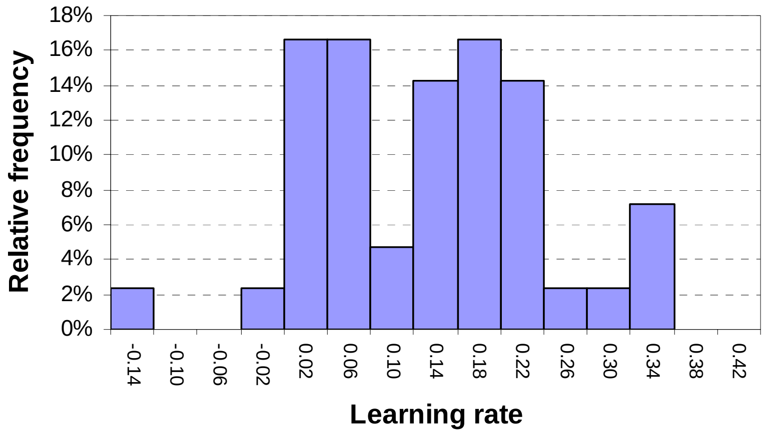

Figure 4. Distribution of learning rates in 42 energy technologies (McDonalds and Schrattenholzer, 2001)

Interpretations of learning curves must consider the market effects and the consequences of fundamental technology changes. Both these effects are discussed in “Experience Curves for Energy Technology Policy” (IEA, 2000, pages 33-40). One of the case studies discussed in this book illustrates the effect of a technology structural change (pages 45-52). The findings are briefly summarised here; the reader is referred to IEA(2000) for details.

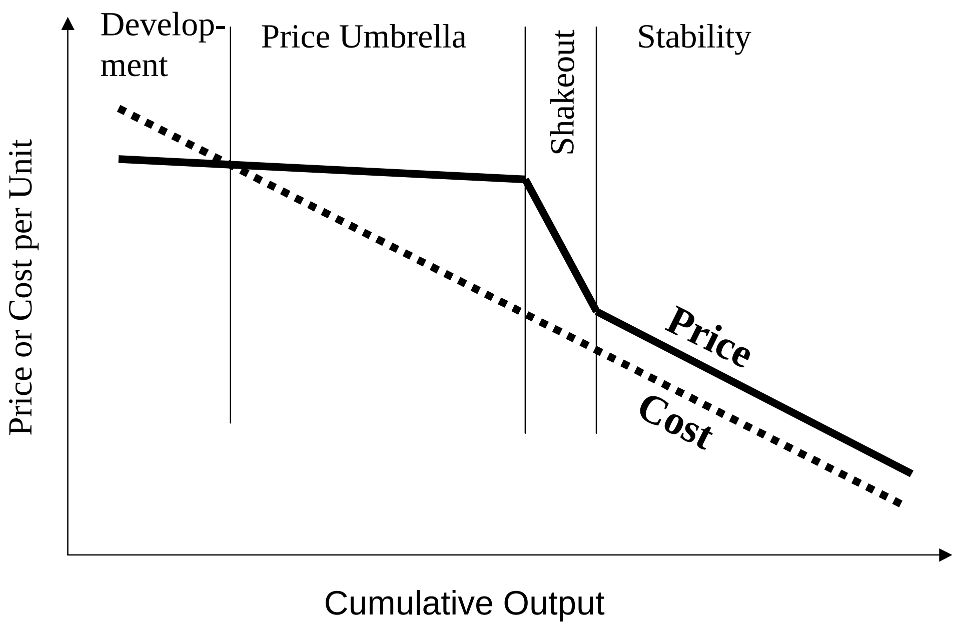

Figure 5. The price-cost cycle (Boston Consulting Group, 1968)

We can usually observe prices in the market, but cost data are usually very difficult to obtain. Therefore, experience curves usually measure prices, but in a market in equilibrium we expect cost and prices to appear as two parallel lines in a log-log diagram. The ratio between them indicates the profit margins in the industry. The Boston Consulting Group (1968) has studied the effect on the price experience curve in markets, which are initially not in equilibrium and Figure 5 summarises their findings. The different price regimes are discussed IEA(2000). The "Price Umbrella" show the advantages for the first mover.[1] During the "Shakeout" period the learning rates may be very high (more than 30%) but they of course do not indicate technology learning but market adjustments. It is dangerous to base technology forecasts on experience curves measured over short periods of time which may include shakeout. This is an important pitfall in experience curve analysis.

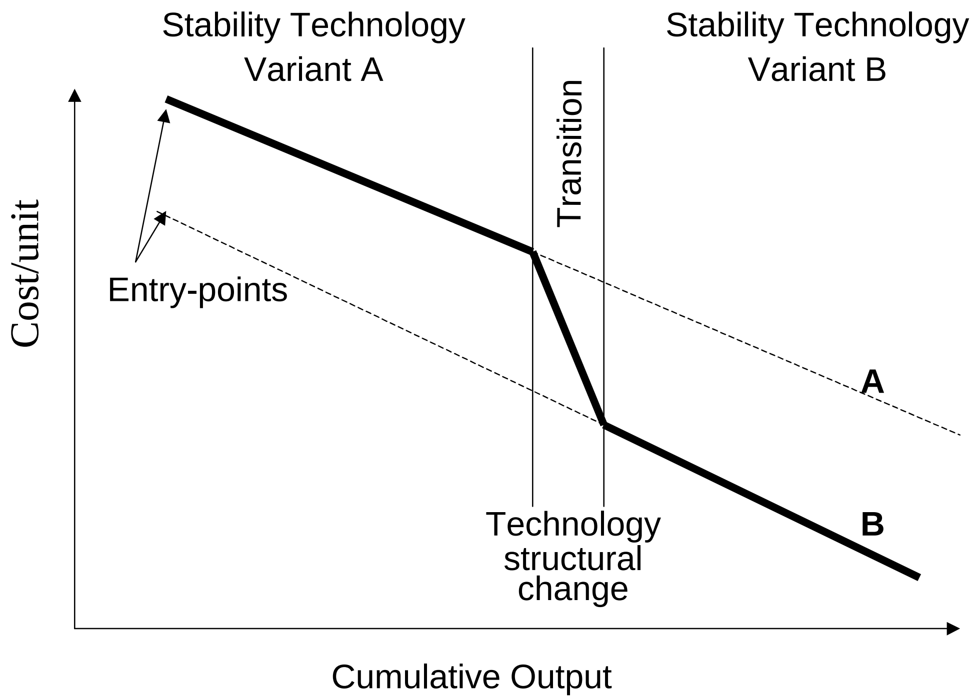

Figure 6. Effect of a technology structural change on the experience ***cost*** curve.

Figure 6 shows the effect of a real fundamental technology change, which very quickly is adopted by the market. Note that the effect of a market shakeout and a technology structural change may be the same in the experience price curve! To verify that a fundamental technology change has happened it is desirable to have both cost measurements and a technology bottom-up analysis.

2.2. Generation of Technology Learning Scenarios

The purpose of the scenarios is to "bracket" reasonable outcomes of continuous technology progress for the estimates of future investment costs. The work by Dutton and Thomas, and by McDonald and Schrattenholzer provides us with tools to define base scenarios. Ideally, the *ex post* analysis should make it possible for us to decide whether the technologies should be classified as "new" or "grafted". We should then be able to confront our forecast based on the experience curve analysis with the Delphi estimates and from this dialogue come up with probable future learning parameters and uncertainties in these forecasts.[2]

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[1] Many leading brand names are incorporating the ideas of figure 5 in their corporate strategies. This was shown in a very convincing way by one of the speaker at the IEA Workshop on "Technologies Require Markets" in November 2001. See also "Creating Markets for Energy Technologies", IEA 2003, footnote 21 page 60.

[2] Note that scenarios provide learning parameters, not price tracks. There is nothing like a forecasted price track in the experience methodology. Future prices are a result of two different assumptions: learning parameters and deployment of the technology. The logic of technology learning is that the market creates its own prices from deployment of various technologies.

However, as will be seen, the ex post analysis indicates strong influence of both market and technology change effects (figures 5 and 6 above). 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(2000)). Further studies with literature search, interviews with industry representatives and longer data time series could considerably improve the ex post analysis, but this would require more resources and time.

Using available time and resources, I use four different scenarios to bracket the effects of technology learning on the investment estimates:

- *Delphi:* the implicit learning parameters is extracted from the estimated future prices and the WEO results on physical capacity expansion (deployment of the technology).
- *Dutton-Thomas*: technology learning characterised by a learning rate of 18%, which is the most probable value in the Dutton and Thomas distribution.
- *Grafted*: technology learning characterised by the low learning rate in the second peak in the distribution presented by McDonald and Schrattenholzer. I consider this emblematic for a technology grafted to an existing well-established technology.
- *Ex Post*: technology learning characterised by the learning rate observed in the ex post analysis. As these learning rate are very high, I consider this as a technology optimistic scenario where the sustainability of such high rates must be scrutinised.

2.3. Calculation of Global Prices and Total Investments

The calculations of prices and total investments follow simply from the assumptions about technology learning in the different scenarios and from the deployment rates in WEO(2000).

3. Experience Curve Analysis for the Technologies

3.1. Liquefaction Plants

There are three available time-series data sources for this technology: Gas Technology Institute (GTI 2002), BP (2002) and Standards and Poor (2001). GTI and BP cover the period 1965-2001 and Standards and Poor 1998-2001. They all agree, so at this stage I see no reason to search other time series. If further work is needed, one probably has to pass on to project level.

Figure 7 shows the experience curve analysis based on GTI(2002). Assuming a standard experience curve provides a progress ratio of 72% (LR=28%). The fit is not particularly good with an R2=0.7963, which in itself is not alarming considering that we are dealing with individual projects where the site conditions may vary quite a lot. However, there seems to be systematic deviations indicating that the standard analysis does not capture either market conditions or technology learning correctly. Fitting a knee-shaped experience curve as discussed above seems to provide a much better fit. The progress ratio 1965-1988 seem very reasonable, 81%. But the slope of the curve in the 90s signals either that our analysis is wrong or that there were very fundamental changes in markets or technologies after 1988. There are three possible explanations:

- *Shakeout*. This means that the market was too elevated before 1988. Against this argues the fairly normal behaviour 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 spillover and technology transfer.
- *Technology Structural Change*. Figure 8 shows an effort to test this hypothesis. The proxy for industry experience, namely the cumulative installed capacity is set to zero in 1987 and we suppose we start learning with a completely new technology from this year on. This gives a learning rate of 28% (PR=72%), which is on the high side but not unreasonable.
- *The Output from the Learning System is Systematically Changing*. This means that the product "Liquefaction Plant" is not the same in 1990 as in 1980, we are not "comparing like with like". 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 9 is a first effort to test this hypothesis. Far East was important both before and after 1988, and expansion investments in the Badak site in Indonesia have been considerable after 1988. However, investments in new sites in the Middle East were as important as possible expansion investments during that period.

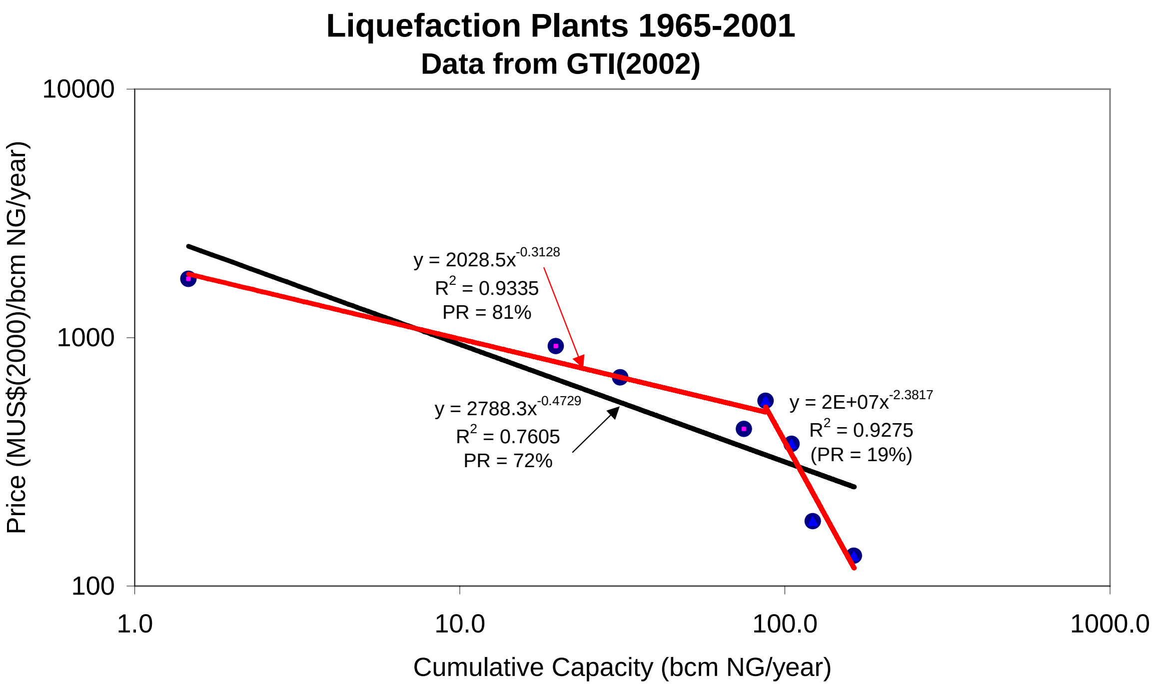

Figure 7. Experience Curve analysis for Liquefaction Plants

Considerably more work is needed to resolve which hypothesis or mixture of hypotheses is correct. For our immediate purpose this does not seem necessary; figure 7 contains sufficient information to start discussing technology learning scenarios. The fit for the period 1965-1988 provides a Dutton-Thomas scenario with a learning rate of 19% (PR=81%). None of the three hypotheses argue that the strong cost reductions in the 90s will continue. Both the standard experience curve and Figure 8 place a strongly technology optimist scenario at a learning rate of 28%.

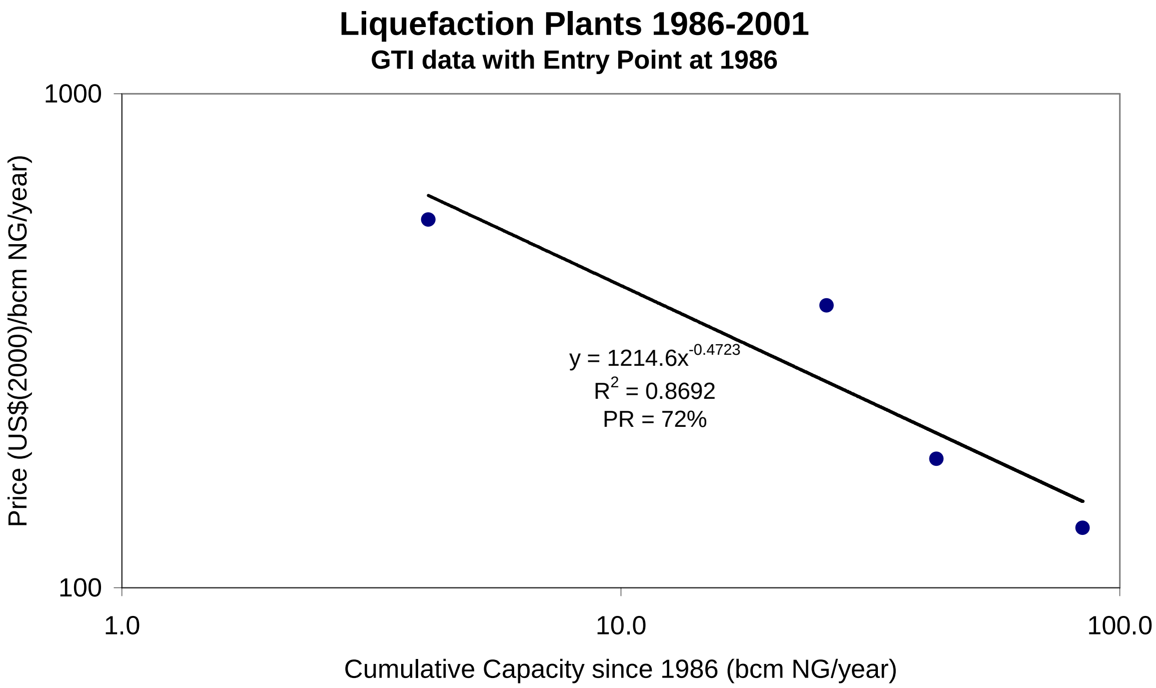

Figure 8. Experience curve assuming a fundamental technology change in 1986.

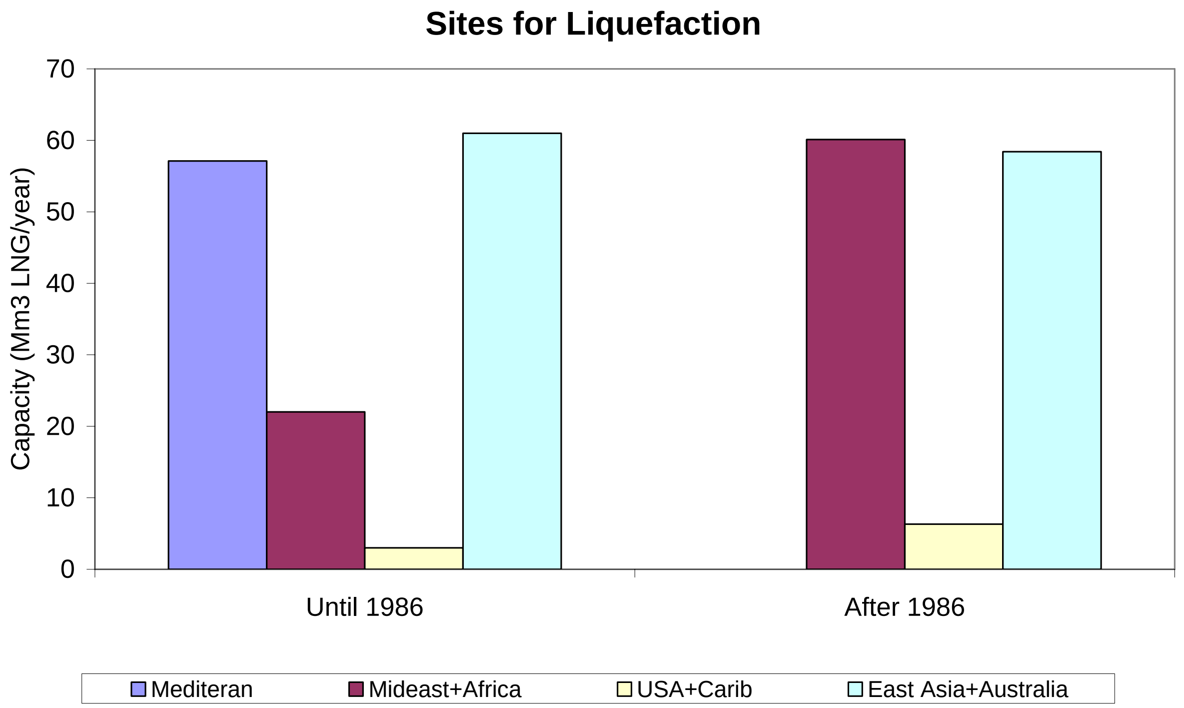

Figure 8. Sites of Liquefaction plants

The analysis indicates that the Grafted technology scenario should be considered as "technology pessimistic". The learning rates implicit in the Delphi estimates are calculated from Laura Cozzi(2003) and WEO(2002) deployment rates.

The learning parameters for the four scenarios are thus:

Table 1. Liquefaction Plants: Scenario Parameters

Scenario	Delphi	Dutton-Tomas Most probable	Grafted Pessimist	Ex Post Optimist
Learning rate (Progress ratio)	17%(83%)	19%(81%)	5%(95%)	28%(72%)
Entry point in 2001:				
Price		178.6 M$(2000)/bcm/year		
Cumulative Capacity		163 bcm NG		

The price at the entry point in 2001 is not the same as in the data from GTI. The entry point at 2001 used for all the four scenarios represents the average of eight recent projects or planned projects, which gives it a high validity. However, it is 30% higher than the value given by GTI for 2001. This can be interpreted as meaning that a correction to the steep fall in prices is already taking place and that the slope observed for the 90s cannot be sustained. But it could also mean that the choice of entry point for the introduces a ***systematic*** uncertainty to the estimates. This uncertainty is of the same order of magnitude as the uncertainty in technology learning. The choice of representative price in 2001 warrants further discussions but does not influence the learning parameter for the four scenarios.

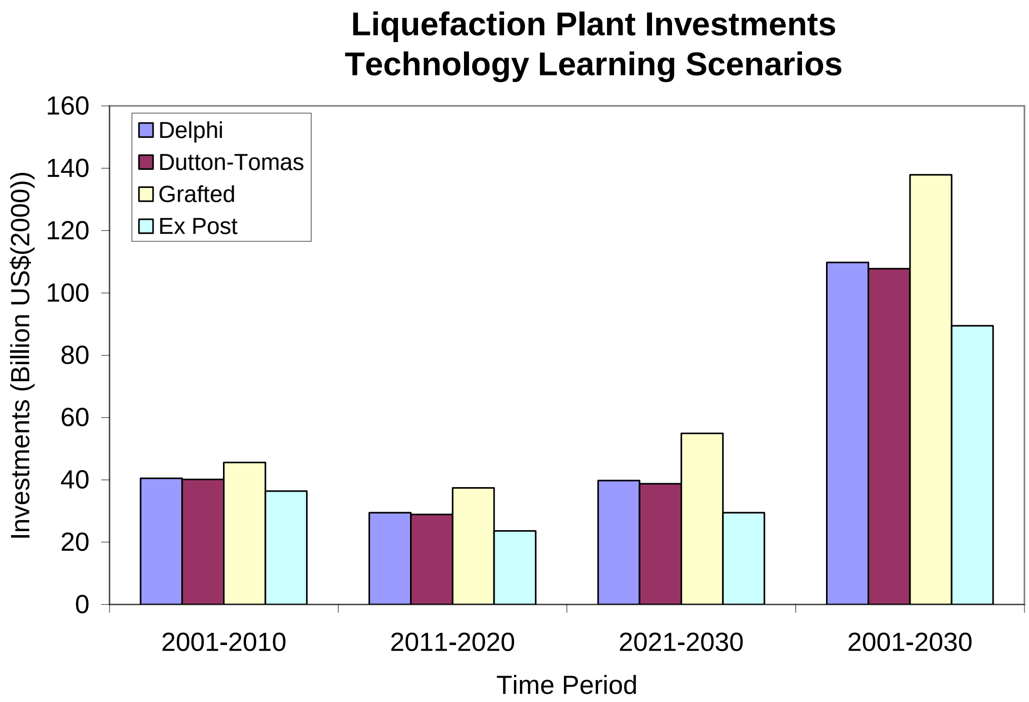

Figure 10. Summary of technology learning scenarios.

Figure 10 shows the investment costs in the four scenarios. Based on those scenarios we thus conclude that the total global investment needs for liquefaction plants are 89-138 billion US$ with a most probable value around 110 billion US$.

2.2. LNG Tankers

There are three series of price data available: GTI(2002), Cedigaz(2002?) and Standard and Poor (2001). There are two problems with the data sets: the prices are given as M$/vessel and there is only one reliable data point before 1991. The size of vessels vary considerably, which means that prices implicitly reflects economies of scale but the cumulative number of tankers used as proxy for the experience do not. This makes it difficult to benchmark the obtained learning rates. To solve this problem properly I need to find the capacity of each ship. There is no time for such research, so I try to handle this problem approximately below.

Figure 11 shows the data from GTI(2002). The data covers only the period between 1991 and 2001. I have assumed that no tankers with capacity less than 96,000 m3 LNG were built during this period and have excluded tankers less than 96,000 m3 when calculating the cumulative tankers built.

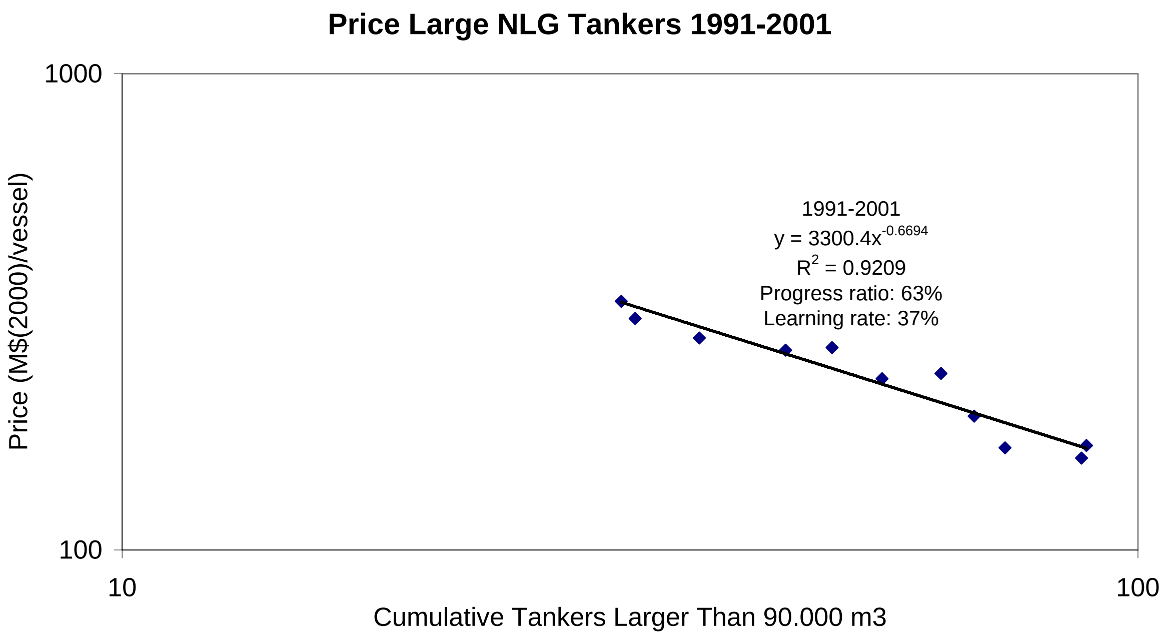

Figure 11. Experience Curve 1991-2001

The learning rates are excessively high although not so unreasonable high as for liquefaction plants during the same period. The Cedigaz data series has one point at 1975 which modifies the analysis and provides a learning rate of 30% if the basis for experience is all vessels built since 1975 (excluding renamed vessels!). It is however, not possible to see if there is a knee in the curve as for liquefaction plants.

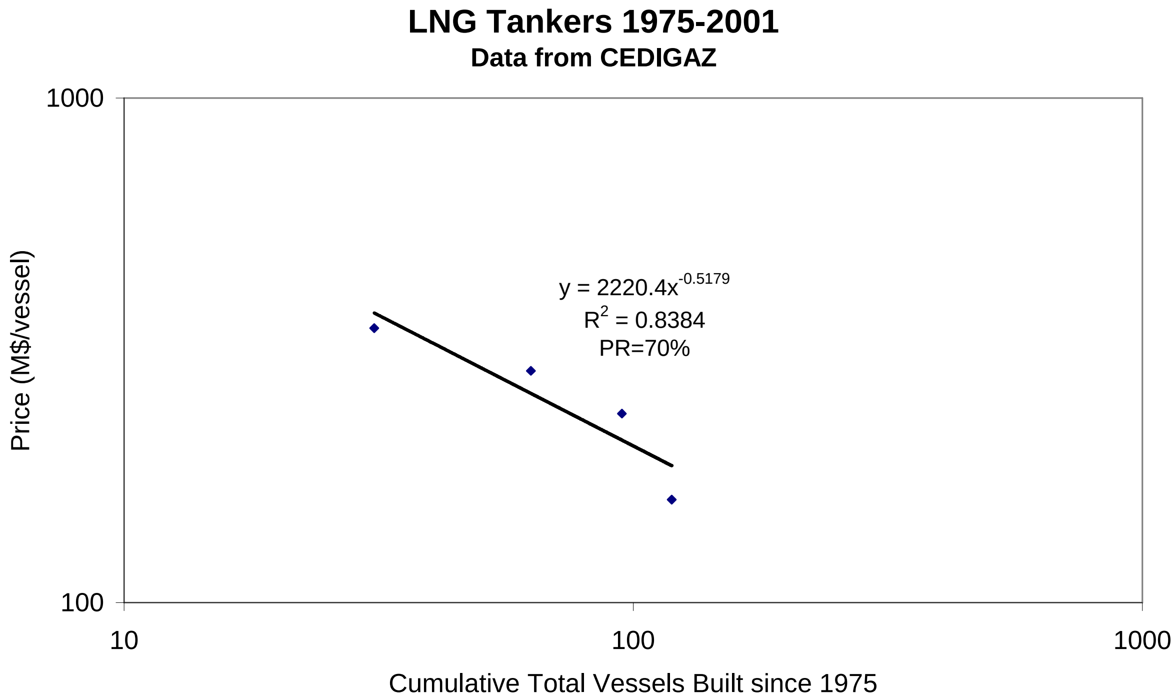

Figure 12. Experience curve for total vessels built.

The same hypotheses as for liquefaction plants could be forwarded to explain the high learning rate. One could easily envisage market effects in the highly competitive and global shipbuilding industry scrambling to position themselves in a future prospective market (including state subsidies). However, the literature indicates that there has been considerable technical progress in the 90s and that there are several technologies competing for implementation in future tankers. Resolving the experience curve in figure 11 into curves for these technologies would help leverage forecasting for this technology. At the moment we have to proceed with the data at hand.

For the four scenarios, I use the Cedigaz results to generate an Ex Post Technology Optimist scenario.

As entry point for experience in 2001, I use all vessels built since 1975 (excluding renamed vessels). For calculating future prices, this is a conservative choice because using the experience in figure 11 would make the technology "younger" and thus each new ship built after 2001 would lead to a larger reduction in price. The choice for the scenarios is consistent with the analysis of the Cedigaz data. It must be pointed out, however, that the arguments for the Dutton-Thomas scenario and the Grafted scenario will remain methodologically unclean as long as 'Cumulative numbers of vessels' is used as a proxy for experience. It is clear that for a more detailed forecast of the cost of the future LNG tanker fleet, such ambiguities must be resolved. But for the Investment book purpose, this amount to a discussion about a possible bias in the uncertainty estimates, and the need to resolve this bias must be weighted against other needs.

Table 2. LNG Tanker Fleet: Scenario Parameters

Scenario	Delphi	Dutton-Tomas	Grafted Pessimist	Ex Post Optimist
Learning rate (Progress ratio)	14%(86%)	18%(82%)	5%(95%)	30%(70%)
Entry point in 2001:				
Price		180 MUS$(2000)/vessel		
Cumulative Capacity		120 vessels (new built since 1975)		

The scenario parameters in Table 2 generate the investment needs in Figure 13.

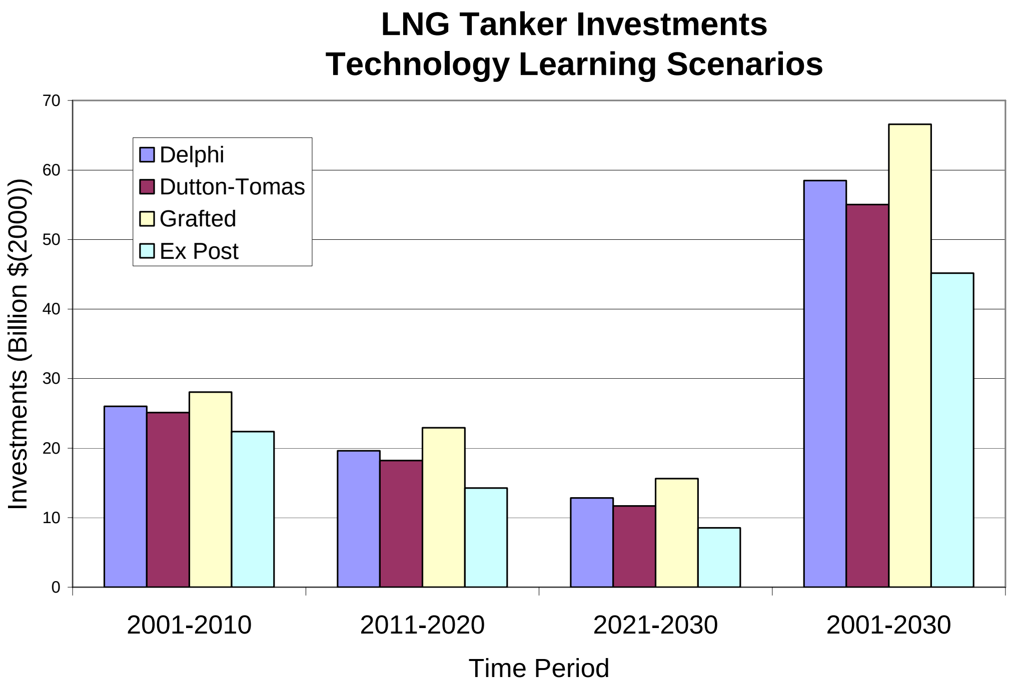

Figure 13. Summary of Technology Learning Scenarios

3.3. Regasification Plants

The only available time series data on regasification plants comes from Cedigaz. and indicates that the cost of regasification plants has been reduced by 90% between the beginning of 1990s and the beginning of 2000s. If this is reflected in capital costs, it implies a learning rate of 31%, which as for the rest of the LNG chain during 1990 is a very high rate.

The price entry point at 2001 chosen for the scenarios is an average of 10 recent or planned projects. An analysis of the project costs shows a strong economy of scale for the regasification plants, see Figure 14. A similar analysis of liquefaction plants does not reveal the same strong dependence on scale. The price at 2001 corresponds to an average plant capacity of 6 billion m3 of natural gas per year. It is interesting to note that the economy of scale parameter is 0.7622 quite close to the value of 2/3 which is usually reported in the literature.

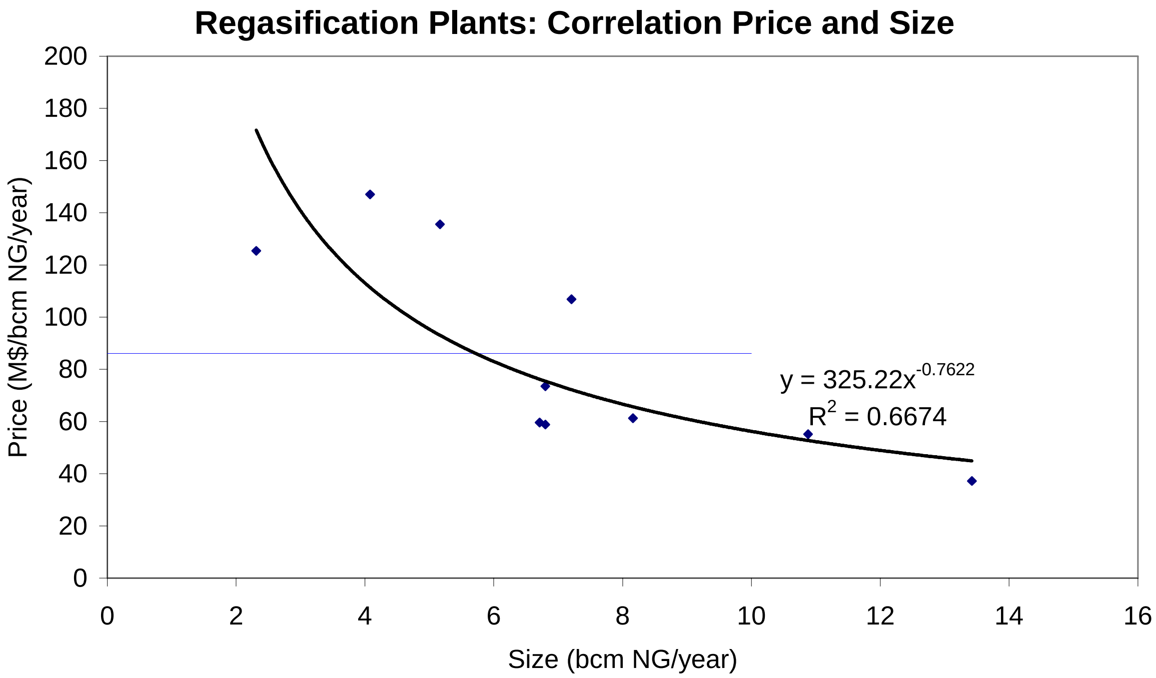

Figure 14. Economy of scale for regasification plants

The scenario parameters for regasification plants are given in Table 3.

Table 3. Regasification plants: Scenario Parameters

Scenario	Delphi	Dutton-Tomas	Grafted Pessimist	Ex Post Optimist
Learning rate (Progress ratio)	24%(76%)	18%(82%)	5%(95%)	30%(70%)
Entry point in 2001:				
Price		86 MUS$(2000)/bcm NG/year		
Cumulative Capacity		336 bcm NG/year		

Scenario results for regasification plants are presented in Figure 15.

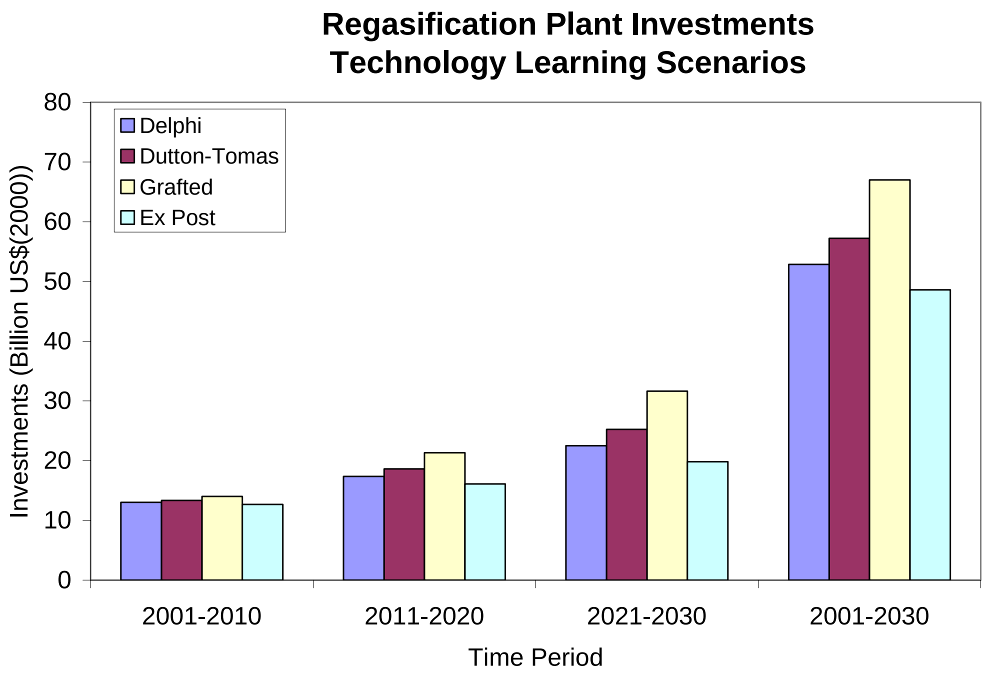

Figure 15. Summary of technology learning scenarios for regasification

4. Conclusion

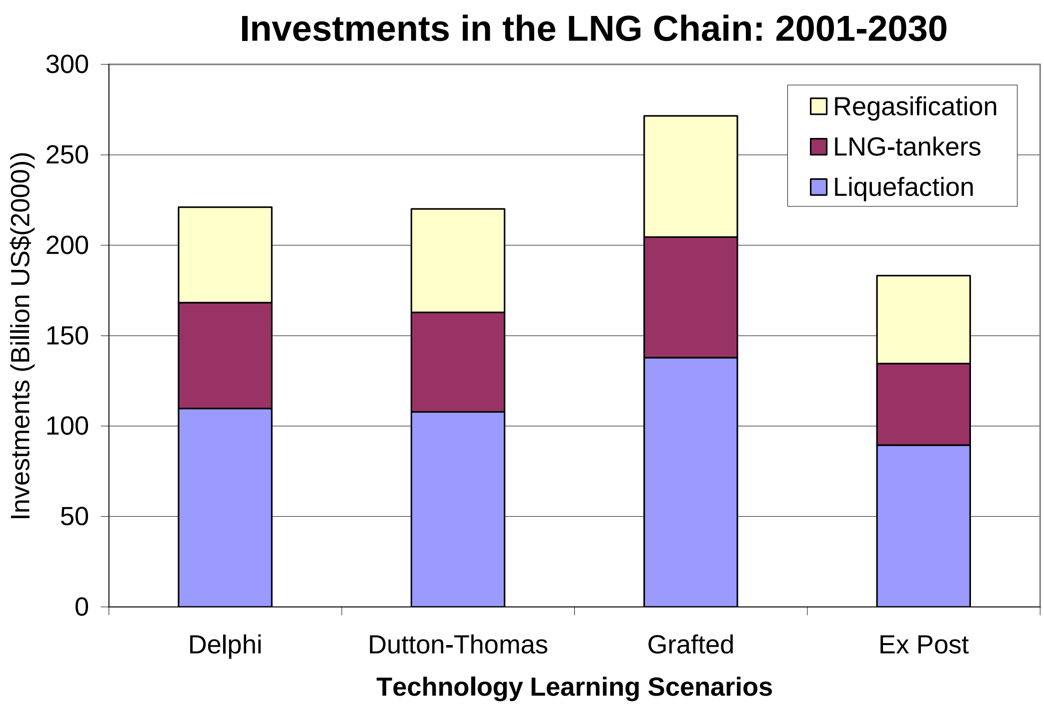

Figure 16. Summary of results from the technology learning scenarios.

Figure 16 shows the investments in the total LNG chain over the thirty-year period 2001-2030. The total investments in the Delphi and Dutton-Thomas scenarios are the same, but the two scenarios differ for the three links in the chain. A very preliminary conclusion is that the total investments in the LNG-chain will be 220 billion US$(2000) and that the interval 180-270 billion US$(2000) captures the difference between the technology optimist and the technology pessimist.

However, the analysis above also elicits some issues which need to be clarified. Some of the issues may need further discussions in the Investment book process, others to help to understand in more detail what is at stake in expanding the LNG chain. I summarise the findings below:

- *Price for Liquefaction Plants in 2001*. The entry value for investment price used in the analysis differs considerably from the value for 2001 given by all three data sources quoted in section 3.1. Using the value from GTI(2002) would reduce the total cost for the LNG chain by 15%. The value used by Laura Cozzi(2003) and adopted here has strong backing and is interpreted as a correction to the very strong cost reductions during the 90s. But considering the importance of this number, it may be resource-effective to try to clarify the discrepancy.
- *Source of cost reductions in the 90s*. All the three technologies in the LNG chain show strong cost reduction in the 90s with learning rates considerably in excess of the most probable values in the Dutton-Thomas or McDonald-Schrattenholzer distributions. Finding the sources of these reductions would improve the precision in the technology forecasting. Section 3.1 provides three hypotheses for the reductions: market and technology effects and systematic changes in the product from the learning system. These hypotheses can be applied to all three technologies and could serve as a starting point for a detailed analysis.
- *Proper representation of experience for LNG vessels*. Using vessels as output from the learning system producing LNG vessels does not properly capture economies of scale, and will tend to overestimate learning rates. The benchmarking of the learning rates to the Dutton-Thomas or McDonald-Schrattenholzer distribution is not evident. Using a true capacity representation would facilitate interpretation of the result of the Ex Post analysis and strengthen the technology forecast
- *Discontinuous technology change*. The analysis assumes that technology progress is continuous and that the roles of the three links do not change. It is conceivable, e.g. for safety reasons, regasification is made on board the LNG tanker and fed into off-shore pipelines.

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