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Learning from the Sun

Analysis of the use of experience curves for energy policy purposes: The case of photovoltaic power. Final report of the Photex project

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Acknowledgements/Preface

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Abstract

Since the 1990s energy policy scientists have started to explore the possibilities of using the experience curve approach for energy policy making. The concept of the experience curve is simple, at least in principle. It states that, for every doubling of cumulative produced capacity of a product or technology, the cost for making it declines with a fixed percentage (learning rate). Historical statistical analysis can be used to define this percentage. Extrapolating the trend thus found, into the future will then give relevant information about future cost developments and will also give information how much 'learning money' will be needed to get to the break-even point. The Photex project used the development of solar PV as a case to further explore this approach, and also to deduce lessons for PV policy. Other aims were to look at learning rates of the different components of PV-systems and to combine the experience curve analyses with bottom-up engineering studies. The main conclusion with regard to the use of experience curves for energy policy making is that this is an interesting approach, but that such an analysis should be done with much care. For the historical analysis the availability of reliable and firm data is essential. As cost data often are not available, price data could be used as a proxy, as long as sufficient long time ranges are used. Also, the analyst should take care he considers the right learning system boundaries. Furthermore the number of years to be included in the statistical analysis should at least be 10 years and this period sample should not over-represent stable price periods or periods of steep price decline. If possible, data uncertainties should be taken into account as well. An interesting finding was that, at least in the case of PV, the learning rate is not a constant, but can vary over time. In the case of PV it improved from 20% to 23%. Extrapolations into the future should take uncertainties into account and always be done scenario-wise. Doing this for grid-connected PV, the analysis shows that self-sustaining markets could be expected in Europe at specific locations before 2010. Reaching break-even for the wholesale electricity market will most probably not happen before 2030. To reach break-even within a reasonable time-frame, the market deployment growth rate should be at least 15%-20% over the next coming decades, assuming that the learning rate remains at the current 20%-25%.

Because the learning rate is not fixed, it might be possible to influence it by a right combination of market deployment policy (learning investment) and R&D-policy supporting the market development (investment in learning). An experience curve analysis can contribute interesting information to policy discussions on the balance between market support and R&D. In the case of PV it seems that a substantially increased support for learning processes, such as R&D, and interactive learning networks within and between users, producers and component suppliers, which supports current and future market deployment instruments, can yield a huge public benefit in the longer term. Furthermore the experience curve approach shows that from a European perspective the cost-effectiveness of PV-policy could be improved. This effectiveness could be reached if a European-wide market-based incentive scheme were implemented. As cost-effectiveness is just one policy goal among many others, such a European market-based deployment instrument should not exclude additional Member State PV deployment policies.

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1. INTRODUCTION

1.1 Purpose and objectives of the project

What can energy policy learn from experience curve theory?
The saying "experience improves performance" has been quantitatively analysed in industrial environments since the 1930s and has become a standard strategic assessment tool since the 1960s (see IEA, 2000). The quantitative phenomenological relationship that is described is called the 'experience curve' and its mathematics is rather simple, at least in principle: for every doubling of cumulative production of a product, the cost declines with a fixed percentage. When sufficient historic data are available, the fixed percentage ('learning rate') can be determined and companies can assess what cost impacts might be expected in the longer-term future, given certain growth scenarios.

When the concept of experience curves is taken from the level of the firm to the level of an industry or an industrial sector, the question arises to what extent the experience curve approach can be used for policy purposes. The use of experience curves for policy purposes in the field of energy is a topic that has been taken up in recent years, first as part of research programmes of universities and research institutes (e.g. Messner (1997), Ney (1997), Mattson (1997) and Matson and Weene (1997)) then on instigation of the IEA (IEA 2000), but also as a primary topic in EU-funded research projects (see e.g. Seebregts et al. (2000), Kram et al. (2000) Ney et al. (2003) and Kouvaritakis et al, (2000)). Questions relevant for policy include: can the use of experience curves help us in assessing future cost trends of energy technologies, the amount and timeframe of government support needed for certain technologies and the effect of R&D and market stimulation programs? And under what conditions?

Photovoltaic technology as an interesting case
The main aim of the EU-funded project Photex is to contribute to this discussion by researching a specific technology as an in-depth case (Photo-Voltaic solar energy technology or 'PV'). This follows the line of another EU-project (EXTOOL) that focused on Wind energy technology.

PV is an interesting case for several reasons: The history of PV-market stretches back several decades (since the 1970s) so that sufficient statistics can be expected. Furthermore PV-technology consists of many components. Relating learning-by-experience at the PV-system level to learning at the component level could give more insight in how experience curves work and can be used for policy analysis. Also, PV is seen as a 'promising technology' in the framework of a transition to a cleaner energy system in the longer term, and is therefore subject of active energy policy in many EU-Member State countries.

Main objectives of the Photex project
In order to contribute to the discussion on what energy policy can learn from experience curve theory by researching the PV case the main objectives of the project were:
1) to collect data on cost and production for PV systems and PV components. The primary data have been put in a database;
2) to derive experience curves from these and use the experience curves to assess PV policy programs and
3) to disseminate the insights gained within the project among PV industry actors and policy makers.

Scientific objectives: further development of experience curve methodology
An explicit objective of the Photex-project also was the further development of the experience curve methodology for energy policy uses. The scientific objectives were:
- to further develop the experience curve methodology as a quantitative tool for strategic assessment of emerging technologies.

- to develop the experience curve methodology as a tool to analyse the impact and the cost effectiveness of different energy and RTD policy programmes for emerging technologies.
- to analyse the advantages and disadvantages, and the potential and limitations of using experience curves as a tool for energy and RTD policy assessment.

1.2 Experience curve concepts in short

The mathematical relationship between cost and deployment is a straight line on a log-log scale
Experience curves describe how cost apparently declines with cumulative production, where cumulative production is used as an approximation for the accumulated experience in producing and employing a technology. A specific characteristic of experience curves is that cost declines by a constant percentage with each doubling of the total number of units produced, see Figure 1.1. The observed cost reduction for different technologies cover a range from approximately 0% to 35% (the 'learning rate') for each doubling of the total number of units produced (see e.g. Argote and Epple, 1990).

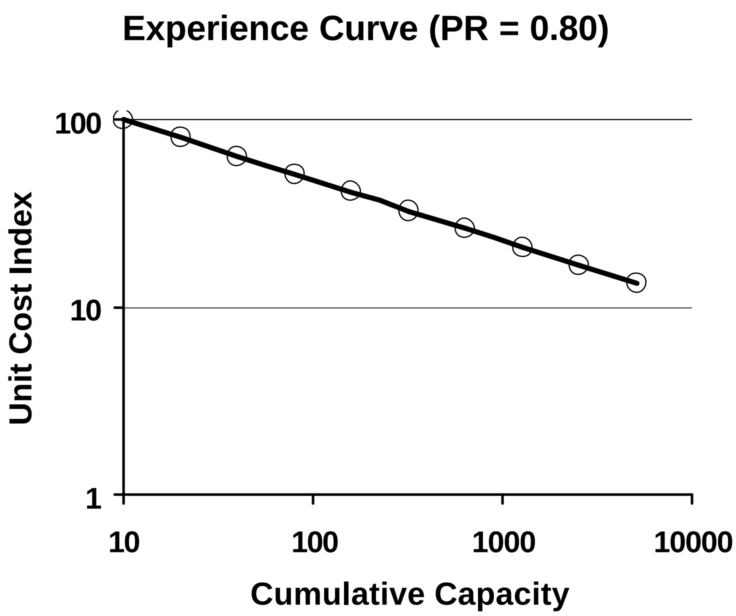

Figure 1.1 *Example of an experience curve*

The cost reductions in the experience curve refer to total costs and changes in production (process innovations, learning effects, and scaling effects), products (product innovations, product redesign, and product standardization), and input prices. In all, gaining experience is a long-term process that represents the combined effect of a large number of parameters, which may undergo fluctuations over short periods. Only after many doublings of experience can the underlying pattern or trend be distinguished.

The progress ratio is equal to 1-learning rate
If after one doubling of production the cost is 80% of the costs before the doubling (i.e. a decline of 20%, which means a ***learning rate*** of 20%), the technology is said to have a ***progress ratio*** of 80%. Thus the progress ratio is equal to a 100% minus the learning rate. The term progress ratio is used most often in experience curve theory, although it can lead to confusion. A higher progress ratio indicates a less favourable technology development than a low progress ratio.

1.3 Learning processes and energy policy

1.3.1 Learning mechanisms

Experience curves reflect outcomes of underlying learning processes. The concept of learning as discussed in theories of technical change is taken very broad and is more or less equal to innovation. Currently four types of primary learning are normally distinguished (see e.g. Kamp 2002):

- Learning-by-doing

  This involves learning from experience in production processes. The *know-how* that is produced by experience is often not well documented and can be regarded as tacit knowledge. Know-how resides in individuals, organisational routines and manufacturing practices. Through production experience many bottlenecks are discovered and solved and improvements can be made.

- Learning-by-searching

  Synonym for learning brought forward by R&D. Learning by searching concentrates on developing '*know-why*' knowledge. R&D-activities at universities and research institutes primarily bring it forward and it is often presented in articles in scientific and technological journals. It deals primarily with general concepts and principles.

- Learning-by-using

  Learning that occurs by the utilisation of technologies is especially important when several components have to be combined in using the technology. It is often difficult to exactly define and optimise interactions of many components beforehand, also because circumstances found in practice cannot always be assessed exactly on beforehand. Solutions are found in practice and are optimised according to experience. This knowledge can be described as '*know-what*'. The existence of user groups that interact with each other and with the technology producers can help this kind of learning.

- Learning-by-interacting

  Transfer of knowledge between users, producers, research institutes and policy makers occurs best when there are fruitful and constructive relationships between these groups (see e.g. Lundvall, 1988 and Lundvall 1992). This kind of learning occurs best when actors know whom to address in getting relevant information on problems and solutions. This can be characterised as '*know-who*' knowledge. Especially for tacit knowledge it is important to have large and accessible knowledge networks.

Learning-by-learning

Other authors, also use the concept of 'learning-by-learning' reflexive learning or second-order-learning, indicating that the primary learning processes themselves can improve over time, especially when explicit attention is paid to learning from learning processes, by developing learning strategies, applying and evaluating them (Rotmans and Kemp, 2003).

Learning-by-expanding

Discussions in the Photex project team have led to the suggestion of still another form of learning, which we have not found in literature. This form of learning can possibly be characterised as 'learning-by-expanding' or 'learning-by-network growth' or 'learning-by-embedding'. This concept points to the finding that when a technology is applied more and more, also more actors, organisational structures and industrial sectors become involved in, focused on, dependent on and adapted to the new technology. By learning-by-expanding the learning mechanisms mentioned before are taking place in a larger and larger community.

1.3.2 Learning, experience curves and energy policy

In energy policy (IEA et al) the focus has been on how policy can support primary two learning mechanisms: learning-by-searching and learning-by-doing (see Figure 1.2).

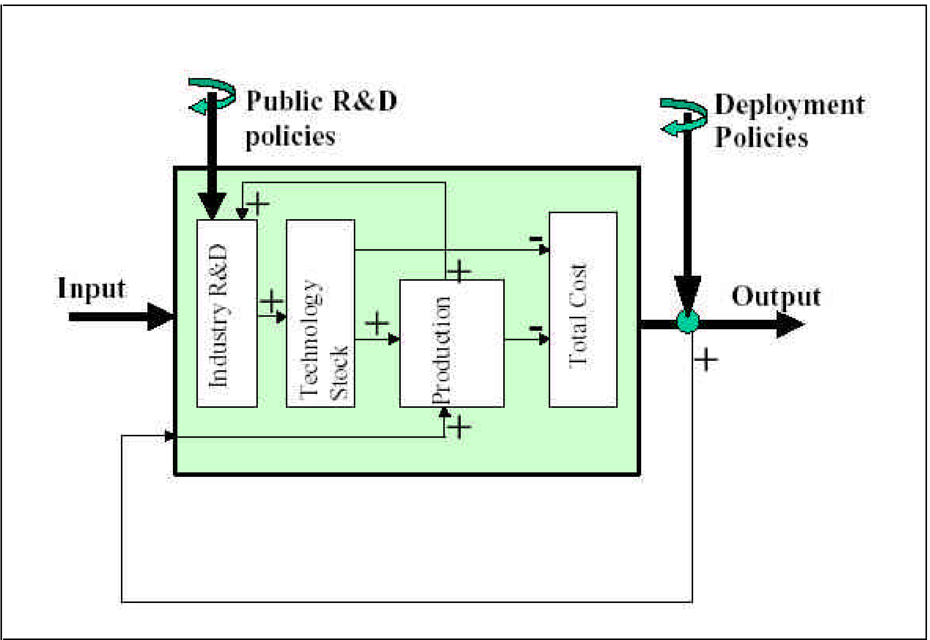

Figure 1.2 *Relationship between R&D and deployment policies (IEA 2000)*

In this picture it is assumed that public R&D focused at a certain topic will also enhance the level of private R&D on that topic. Together they will add the knowledge stock or technology stock of companies. This will lead to lower production costs and a higher level of production. A higher production in itself will also lead to lower production costs. Deployment policies will stimulate production as well. Higher production levels will lead to a higher level of private R&D.

In this way a policy that has a right balance between market support and R&D-support can influence the learning process positively. What exactly a right balance means in practice is still a field unexplored. In this report we will only be able to put some first steps to that analysis.

By taking Figure 1.2 as a starting point automatically the two learning mechanisms learning-by-doing and learning-by-searching have become the main focus points of this research and of this report. However, it is good to realise that they are not the only learning mechanisms and that policy models and structures should be developed to understand and support the other learning processes (learning-by-using, learning-by-interacting and learning-by-learning) as well.

1.4 Potential applications of the experience curve approach for energy policy

Cost projections

One of the possible uses of the experience curve approach is to forecast costs of a technology over time. This means that an additional assumption will have to be made concerning the expected market development. For technologies in an early stage of market penetration this could be done by assuming an average growth rate. The business-as-usual assumption would then be to take the historic growth rate (as is done for PV in Figure 1.3). In section 5.1 we will discuss the use of the experience curve approach for cost projections in more detail.

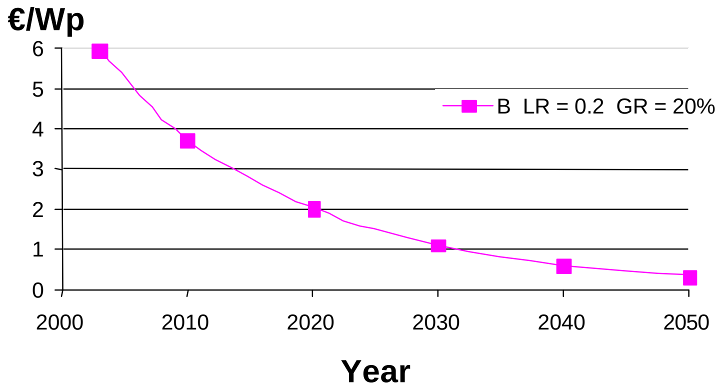

Figure 1.3 *Use of the experience curve in a forecasting mode: PV base case*

If projections are made to a point in time where saturation effects might occur, also a logistic S-curve could be used.

Learning investment and learning capacity
Another possible application of experience curves is to assess how much cumulative financial support will be needed to get a technology to a point where it can compete with conventional technologies on its own. In a log-log diagram this can be visualised as follows:

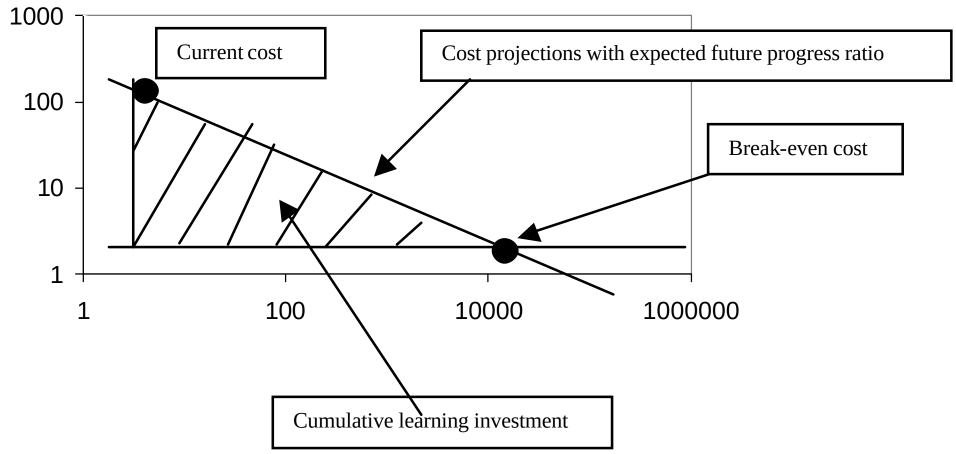

Figure 1.4 *Illustration of the concept of learning investments*

If the projected cost decline follows an expected learning curve, and a break-even price is known, the total learning investment is reflected by the size of the shaded area. The point at the x-axis at which the break-even line is reached shows the installed capacity that will be needed before market break-even is reached (the learning capacity).

Note that break-even prices may depend on the specific market segment.

1.5 Reading guide

In this report, various subjects are analysed, such as the application of experience curves to PV technology, an historical analysis of PV development, and a projection of future deployment possibilities. Since these different subject matters, among each other, vary widely in nature, it is useful to present a short reading guide.

Chapter 2 is mainly dealing with some methodological issues of experience curves

Chapter 3 focuses on the historical analysis of PV technology with the experience approach

Chapter 4 deals with the question whether policy programs in different countries can be related to the historical experience curves analysed in chapter 2.

Chapter 5 gives an overview of how an experience-curve approach can be used for PV price projections. The top-down analysis of the experience-curve approach is supplemented by a bottom-up analysis of technical options to realise the expected cost reduction. It concludes with some considerations on other price-influencing factors for PV up till 2010.

Chapter 6 deals with the question what an experience-curve analysis can provide to the discussion on the right balance between market support (learning investments) and RTD (investments in learning), focusing on the PV-case. A diagram of learning processes in the PV-sector is presented. Furthermore a spreadsheet model, based on the experience curve approach, is described and major results of this model are presented and discussed.

Chapter 7 gives a summary and conclusions of the report.

2. METHODOLOGICAL ISSUES IN HISTORICAL ANALYSIS OF EXPERIENCE CURVES

2.1 Issues encountered in the case of PV

In the course of the project a number of issues were identified which are important when analysing experience curves for PV technology. These points of attention derive from a number observations with respect to PV technology and to experience curve analysis in general:

1. PV systems are compound systems, the composition of which can vary largely between applications;
2. PV system designs may differ between countries because of differences in regulation and market structure;
3. Data on manufacturing costs for PV systems are very difficult to obtain, therefore we generally have to rely on selling price data. Price data, however, are subject to market effects and may therefore show a different trend when considering a relatively short period.
4. Statistical uncertainties are unavoidable. For example: no single price (or cost) figure can be given for a certain year; there will usually be a number of different prices that can be observed in a data set.
5. Currency conversions and inflation corrections cannot be avoided but can also introduce a significant bias to trend analyses.
6. Price and volume data from early, pre-commercial phases in the technology development are rather uncertain but they can have a very significant influence on the results of experience curve trend analyses.

Based on these observation we can formulate a number of conditions and recommendations with respect to experience curve data collection and analysis.

2.2 Conditions for the historic analysis of experience curves

First condition: the availability of firm and reliable data with sufficient detail on PV components
The first condition is that progress ratio estimates should be based on firm and reliable data which include sufficient detail on PV system *components.* In constructing the Photex-database (see section 3.1), we have discovered that this task was far more difficult than anticipated. Total system prices of installed systems are often available, but the cost breakdown into components in many cases has been difficult to obtain. Data on PV-module prices were the least difficult to get, for certain countries. Average module selling price data have been purchased from the commercial company Strategies Unlimited. For components other than modules data are still scarce. Reasons for the difficult availability of data are often related to confidentiality reasons.

Within the Photex project we believe we have finally gathered sufficient data to make meaningful analyses. However, the experienced difficulty to obtain data indicates that for a reliable use of experience curves for policy analysis, regularly monitoring of cost and price data, e.g. by statistics offices would be a great help.

Second condition: Choose the right system boundaries
When analysing experience curves the correct definition of the geographical boundary for the learning system is of great importance. One should realize that technological learning could take place on different geographical scales, for example on a global scale, a European scale or within a single country. The scale at which technological learning occurs will depend on the question whether the targeted market or the product development process itself is bound to a specific region or less so. In addition, the geographical scale, on which the exchange of information between actors takes place, is an important determinant. The choice of the correct geographical scale or - stated otherwise – the system boundary of the technological learning system, is very important if we want to define the

correct measure of the production volume by the same system. Our analysis of the correct learning system boundaries for PV can be found in section 3.2.

Third condition: Historic period of analysis should be at least 10 years and should include at least one complete 'industry cycle'.
As indicated above, real cost data are hardly ever available. What is available are data on prices. In the long run it can be expected that price trends reflect cost trends, but it is known that there is a certain dynamic in this relationship. Prices are determined by supply and demand characteristics and these can be changed in the short term (e.g. by new production plants coming on-line, or by new large market support programmes) by factors not related to the actual cost developments. In the case of PV-technology moving average analyses of the progress ratios have shown that at least a period of 10 years should be taken to get more or less stable results (see also section 3.3).

In addition one should be aware of the effect of 'industry price cycles'. In general the relationship between prices and costs looks more or less like this:

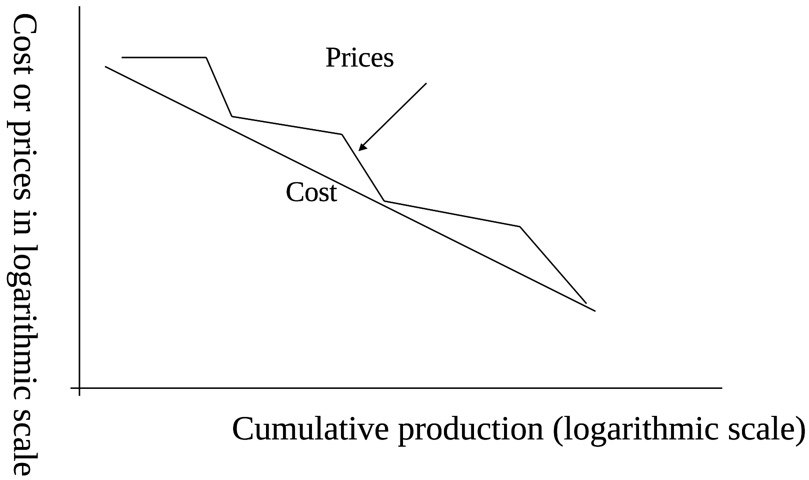

Figure 2.1 *Relationship between prices and costs*

Periods with relatively stable prices (in which profit margins grow, attracting entrants to the market) are alternated by 'shake out' periods with steep price declines (characterised by fierce competition, mergers and bankruptcies of companies). If the historic period on which a determination of the progress ratio is based included an over-representation of one kind of period, progress ratios found might be too optimistic (in the case 'shake-out' periods are over-represented) or too pessimistic (in the case stable price periods are over-represented). In practice it may not always be easy to identify such industry cycles as the may be masked by data uncertainties.

2.3 Recommendations for the historic analysis of experience curves

The experience we got in making experience curves had led to the following suggestions that will improve the practice of experience curve analysis:

Use weighed curves
No single price (or cost) figure can be given for a certain year; there will always be a number of different prices that could be observed in a data set. As a result the average price for a year will usually have an uncertainty attached to it. We have found that these uncertainties can be quite significant and that they should be clearly specified. Where possible the uncertainty data should be included in the trend analysis (as weighing factors). This suggestion has the implication that the requirements for the dataset are enhanced. For every year there should be known a multiple number of primary data points. This is not always available.

Identify uncertainties in trend analysis
Also the results from trend analysis will always have a specific uncertainty. This uncertainty should be clearly presented and included in further analyses (e.g. trend extrapolation).

Use a transparent and consistent way of currency conversion
Currency conversions and inflation corrections can unfortunately not be avoided. Inconsistent application of such corrections may introduce a significant bias to trend analyses, especially when analysing data from a country and a period with a large fluctuation in currency conversion factor rates and/or a high inflation rate (Snik, 2002). Therefore these conversions should be done in a consistent and transparent way, starting from the nominal price data in the original currency.

Within this study all prices are given in Euro for the year 2000. Conversion from local currency for a certain year was done by first applying the GDP deflators from that year up to 2000 and subsequently performing the conversion to euros at either the standard conversion established for Euro zone currencies or the average conversion rate for the year 2000. Furthermore all price data are end-user prices excluding taxes and subventions.

Exclude data from time periods that are dominated by laboratory technology or pilot plants
Price and volume data from early, pre-commercial phases (pre-commercial meaning that there is no market yet, be it a self-sustaining market or a policy-driven market) in the technology development are rather uncertain. For example prices given for photovoltaic cells manufactured in a laboratory environment (i.c. early seventies) are hardly representative for prices in industrial production. Moreover, accurate data on (production) volume for these early periods are quite difficult to obtain. It has been shown that an incorrect estimate for these early data can have a very significant influence on the results of experience curve trend analyses (Snik, 2002). Therefore we recommend to exclude data from such early, pre-commercial phases.

3. HISTORICAL EXPERIENCE CURVES FOR PV TECHNOLOGY

In this chapter we will present the findings of our research on historical experience curves for PV technology. First we will discuss the boundaries of our study and the data collection process. Then we focus first on the results for PV modules, to be followed by an analysis of Balance-of-System prices.

3.1 The Photex database

3.1.1 Study object boundaries for data collection

The method of experience curve analysis has been applied to PV technology already since a long time, but this has mostly been restricted to PV modules. Extending experience curve methodology to the so-called Balance-of-System, that is all system components outside the modules, faces a number of difficulties:

1. First of all there are many different applications with a quite different composition of the Balance-of-System (BOS), such as Solar Home Systems on the hand and multi-MegaWatt grid-connected systems on the other hand. In the first case the BOS will comprise battery storage and a simple charge regulator, while for the large grid-connected system we need array support structures, inverters and control and monitoring equipment. When looking at the cost for the BOS of the latter system type we need to include expenditures for engineering, planning, installation, land purchase, that is cost items which are much less relevant for Solar Home Systems.

2. Secondly, even within one application type such as grid-connected residential systems one can observe significant regional differences in the used system concepts and components, for example due to differences in building codes and building practices, market structure or government interventions.

So an experience curve analysis for the BOS necessarily has to focus on a few specific applications, which are defined narrow enough to have a more-or-less homogeneous set of BOS technologies, but also broadly enough to have sufficient statistics for the experience curve. In this study we will focus on grid-connected systems in Europe[1], which we will further distinguish into residential roof-top systems and large central systems (>100 kWp). For these system types we investigate module and BOS price developments in a number of countries. Also we will look separately at price developments for solar inverters. Some preliminary conclusions will be drawn with respect to module and BOS price development in the considered countries.

3.1.2 Data in the Photex-database

During the project the partners have gathered data and these data have been put in a database. Data collected by PHOTEX is mostly based on individual systems and end user prices. For most of the collected data no cost break down have been available, so the available information is mostly related to total system costs. All price data are end-user prices excluding taxes and subventions. Prices are all stated in Euros for the year 2000 (€-2000), unless stated otherwise

As of June 2003 the overall content of the PHOTEX database is 3,600 records representing about 26 Megawatt of installed capacity. The majority of the data is from European countries. Some data (27 records, 0.5 MW) from Japan could be also incorporated into the data base. The database keeps records of individual system as well as aggregated data e.g. from funding measures.

[1] Because of time and budget constraints we have restricted our data collection effort mainly to systems installed in Europe. Data on stand-alone systems have also been collected for France but these were found to be unsuitable for experience curve analysis because they gave only total system cost.

The Photex database also includes data from the Photovoltaic Power Systems Programme (PVPS), a collaborative R&D agreement, established within the International Energy Agency (IEA). Furthermore list prices for inverters over a period of about 10 years have been included in the database.

Partially the data sets do not have information on price and/or date. For the construction of experience curves it is necessary to have information on time, price, and system parameter e.g. peak power. This reduces the total amount of useful data for experience curve calculations to about 93% of the whole data stock.

The origin of data records by countries in the Photex database is shown in the breakdown according to Figure 3.1. The major part of data is from systems installed in Germany (51%), followed by systems operating in France (28%) and systems in the Netherlands (9%). In this analysis Italy has only a share of 4%. For Germany most data is retrieved from the 1000-roofs-programme and 100,000-roofs-programme, for French systems most data are from the FACE-programme and the HIP-HIP database.

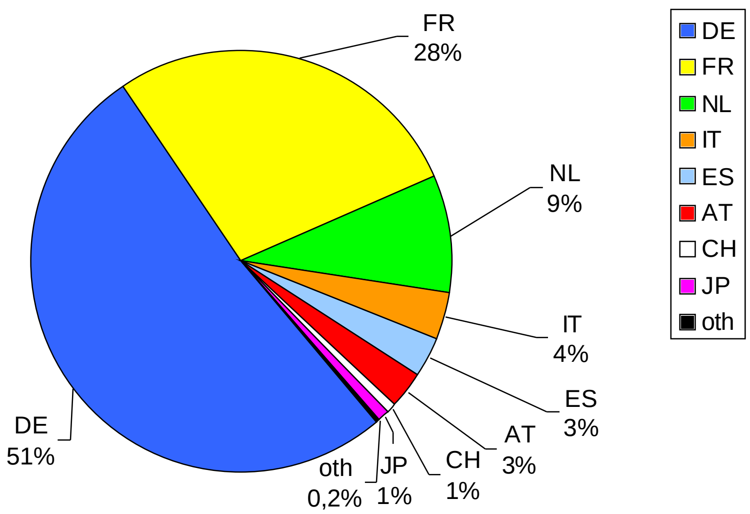

Figure 3.1 *Breakdown of number of systems by country in the Photex database*

Looking at the installed capacity per country in the Photex database the breakdown of shares is completely different. Almost equal shares of installed capacity can be identified between Germany, Italy and the Netherlands, while the French portion has shrunk to only 2%. The reason for this appearance is caused by the average system size in each country. E.g. for France many data is about small systems even with peak power below 100 W, in Italy we have few systems but mostly with peak power above 100 kW up to a few MW. In Germany and the Netherlands most data is on domestic systems with typical size around 2 kW.

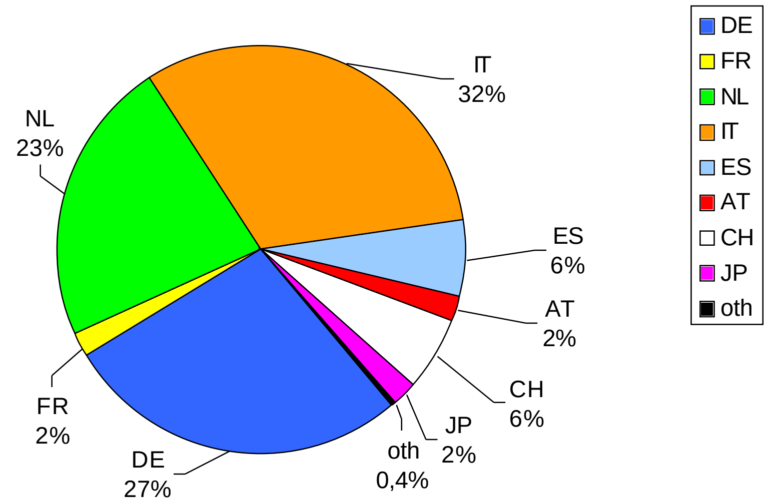

Figure 3.2 *Breakdown by country and installed capacity among the selective countries analysed in the PHOTEX project.*

A breakdown of data share versus year of installation is given in Figure 3.2. The time period before 1991 includes only scarce records, whilst the information from 1991 until 2002 is much better. However, the overall set of data is only a fraction in comparison with the totally installed capacity of PV systems.

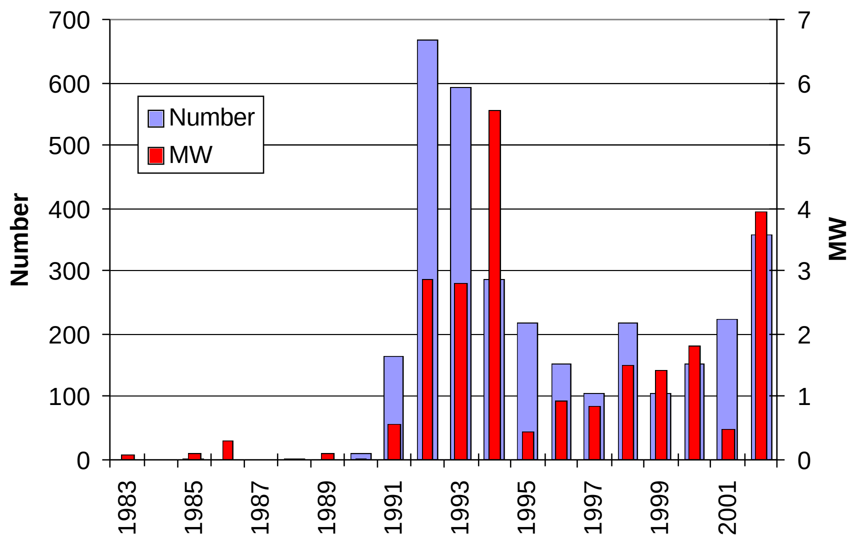

Figure 3.3 *Breakdown of capacity and number of systems by year in the Photex database*

In order to make experience curve for countries as well as for the whole world cumulative installed capacity figures are needed. For this purpose IEA data of PVPS have been used.

Some more details on the structure of the Photex database and the software used can be found in Appendix A.

3.1.3 Data of Strategies Unlimited

As it was difficult to obtain enough data on modules, and as a comparison data source the project team acquired the commercially available database of the US consultancy Strategies Unlimited as published in the report: Photovoltaic Five-Year Market Forecast 2002-2007 published in March 2003. These data have not been included in the Photex-database.

3.2 Learning system boundaries

Modules are part of a global learning system

In the case of PV there are several reasons to assume that PV-module production is part of a global learning system. The product (module) is essentially the same in all countries, Module manufacturing is done internationally operating companies and there is extensive exchange of scientific and technological information on module technology between countries.

If progress ratios for PV-modules are calculated for a single country, the results do vary very much. Countries that have installed more PV capacity than average, will show less favourable (higher) progress ratios, because the price will decline with same pace as in other countries, but the number of doublings will be higher than on the average. In our analyses we have seen this e.g. for Germany and The Netherlands, showing progress ratios for PV modules of around 90% whereas the global progress ratio has been in the range of 75%-80%.

Balance of System (BOS) is part of national learning systems

Other parts of PV-systems, such as inverters, cabling and installation costs, can be seen as part of more local, national learning. There are local actors involved, local products are sold, also because of national building and electrical codes and standards. It must be noted that degree of this local character can change over time and might be different for different BOS-components. During recent years the market for solar inverters has internationalised, at least within Europe. For analyses aimed at the future it might be wise to treat them as global learning components. Within this project we have treated inverters in the historic analyses as part of the national learning systems.

PV-systems should be treated as compound learning systems

The difference in the boundaries of the learning system between different PV system components makes a correct analysis for the learning effect of a compound system like a PV installation rather complex. For the same reason analysis of *total system* price is often *incorrect* and even misleading.

We also give an example how the choice of the learning system boundaries and thus the volume parameter can lead to erroneous and misleading results. If we make an experience curve analysis on *total* system prices (Figure 3.4) we would obtain a PR of 0.862±0.006, that is higher than both the PR for module globally (and in Germany!) and also than the PR for BOS prices. The reason behind this is that we have mixed two learning systems with different system boundaries and thus different volume parameters for the x-axis.

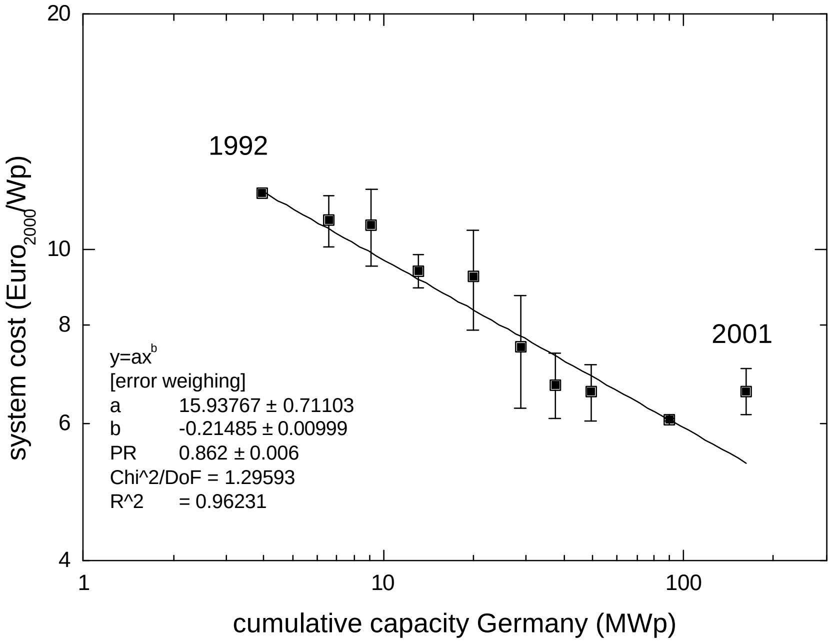

Figure 3.4 *Experience curve for total system prices in Germany, using installed capacity in Germany for x-axis. The analysis of this compound system price gives erroneous results because modules learned on the global market that had a much slower growth than the German market over that period*

Mixing these two systems will lead to erroneous results if the growth on the local market has been quite different from the growth on the global market, as has been the case with Germany.

Sometimes a similar error is made when module prices are plotted versus local volume: again this can give erroneous results if volumes growth rates in the local market were different form global volume growth rates. In this case one ignores the volumes that have been installed outside the considered country and the related contribution to technological learning.

3.3 Price development for modules

Within PHOTEX a moving average approach was applied to identify possible trends in the development of the PR. Based on time windows of e.g. 10 and 15 years, different estimates of the PR can be obtained, using the Strategies Unlimited data for PV-module prices. The one using only the last 15 years 1987-2001 results in a PR of 77%, see Figure 3.7. That value corresponds very well to a recent estimate obtained by (Parente et al., 2002). It should be noted that the period 1987-2001 includes two stabilisation periods and only one shake-out period. This indicates that the progress ratio might even be a little bit lower. It is not certain if this trend is a lasting effect and what the exact cause of the sharper decline is in the recent years is. By analysing moving averages of progress ratios over 10 years we got to the following result:

Figure 3.5 *Results of moving average analysis for the progress ratio estimate*

The graph shows that after a period in which the learning rate for quite some period has been around 20%, during the 1990s the 10-year moving average of the progress ratio started to go up to 25%-30%.

The PV module progress ratio has improved over time from 80% to 74%-77%
Based on the data from the Strategies Unlimited report, the price development of PV modules from 1976-2001 is depicted in Figure 3.7. If we make a regression analysis over the full period we obtain a Progress Ratio of 80.0±0.4%, or a Learning Rate of 20±0.4%. Close observation of the figure reveals periods in which price developments appear to stabilise followed by a period of more rapid price reduction. This suggests that we see here an industry price cycle as explained in Chapter 2. In total almost three of cycles appear to have occurred within the 1976-2001 time frame. As can be seen in the following figure the low value of the 1990-1999 period coincides with a period that does not include a stable price period, so this value of 70% might be overoptimistic. An analysis of the most recent period including one stabilisation period and one price decline period (1987-2001) shows a progress ratio of 77±1.5 %[2]. Results for module price data in the PHOTEX database over the period 1988-2001 (with a smaller part of the first stable price period included) shows a PR of 74%. This result can be considered consistent with the recent SU based data, given the uncertainties and scarcity of the PHOTEX data set.

[2] The difference with result for the complete dataset PR=80.0±0.004 seems to be significant in statistical terms, see also (Parente, 2002)

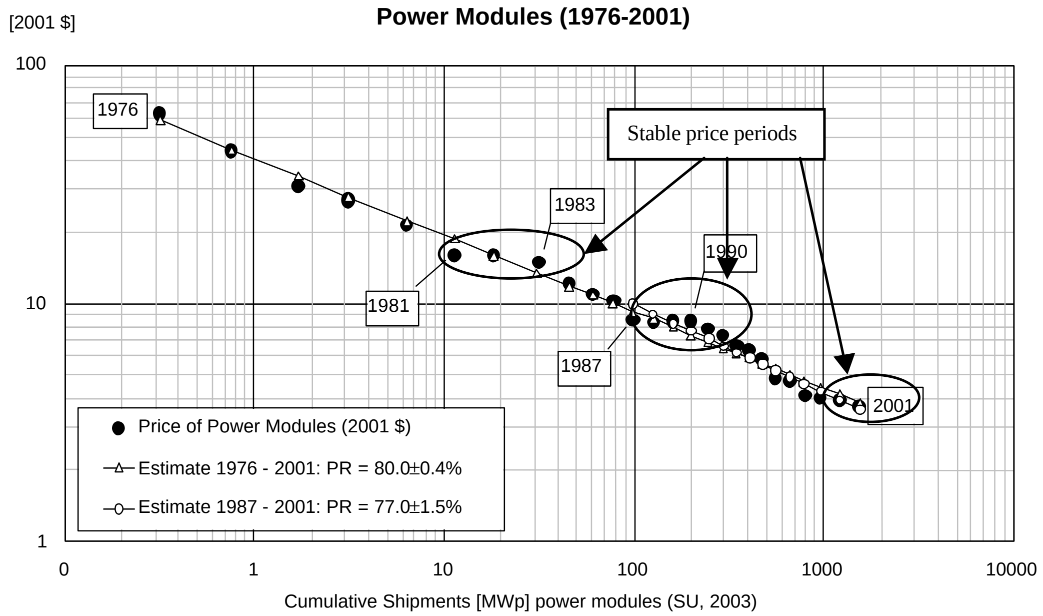

Figure 3.6 *Experience curve for PV-module prices (Global Average Selling Price). Original data from Strategies Unlimited*

Unfortunately Strategies Unlimited supplied no uncertainty information for these module price data.

The improvement of the progress ratio in the 1990s coincides with a time of a relatively lower market growth rate (see Figure 3.7).

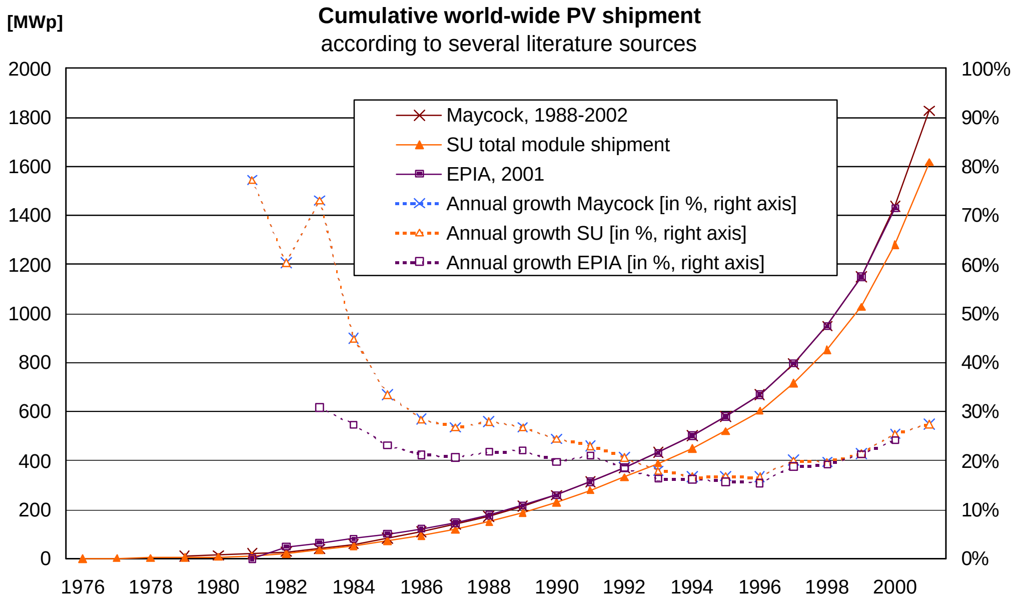

Figure 3.7 *Cumulative worldwide shipments PV modules and annual growth rates, three sources compared: Maycock, SU, EPIA*

In addition, relatively more R&D on PV was spent in the period previous to the 1990s, which started to pay off (see Figure 3.8).

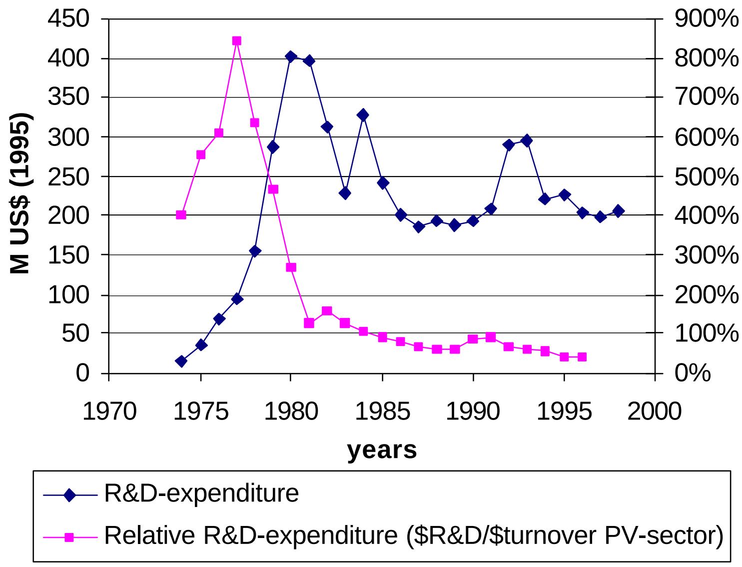

Figure 3.8 *Absolute and relative R&D-expenditures on Photo-electricy energy conversion technologies in IEA countries (Source: R&D-expenditure database from the EU-Sapient project (Criqui et al., 2000) and Strategies Unlimited, 2003).*

Both factors, R&D and a temporisation in market growth, have been a result of policy decisions. This indicates that policy measures can influence progress ratios of technologies, and that a progress ratio is not an intrinsic property of a technology.

Modules are part of a global learning system but local price differences remain

If we compare global average module prices from Strategies Unlimited with those collected for Germany within the Photex project (Figure 3.9) we see a stabilisation and even increase in prices in Germany after 1999. This may be connected to the strong market stimulation in Germany in that period.

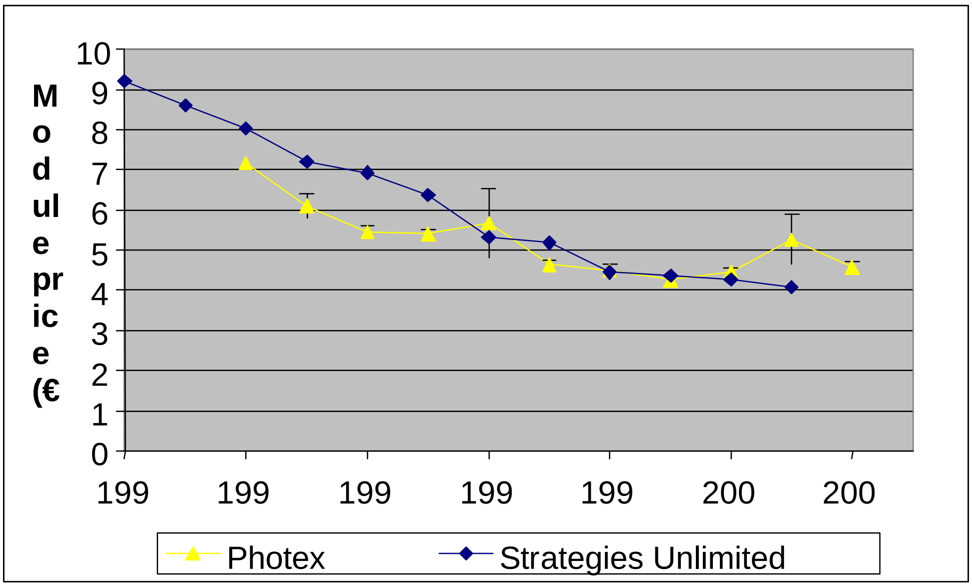

Figure 3.9 *Comparison of average module prices in Germany (Photex database) with the global average prices according to Strategies Unlimited*

Results for module price data in the PHOTEX database over the period 1988-2001 (with a smaller part of the first stable price period included) shows a PR of 74%. This result can be considered consistent with the recent SU based data, given the uncertainties and scarcity of the PHOTEX data set.

3.4 Price development for Balance of System (BOS)

3.4.1 Total balance of system price trends

In the Photex-project the Balance-of-System prices include all costs for PV system components outside the modules, including the installation costs, as paid by the end-user. BOS prices analyses have primarily been done on a country level instead of a global level, since BOS learning is assumed to be bounded by national borders. For residential systems we have done analyses for Germany and the Netherlands[3].

Progress ratio for BOS is about 78% over period 1992-2001 in Germany
Analyses for Germany (1992-2001) indicate that the BOS prices for residential systems had a Progress Ratio of 0.78±0.01 (Figure 3.10), which is surprisingly close to the PR value for modules. Note that we have used the cumulative installed capacity of distributed grid-connected systems (IEA-PVPS data) as the volume parameter on the x-axis. The figure also shows the effect of applying a weighing procedure based on uncertainty data for each data point.

[3] For other countries insufficient data was available for this system type.

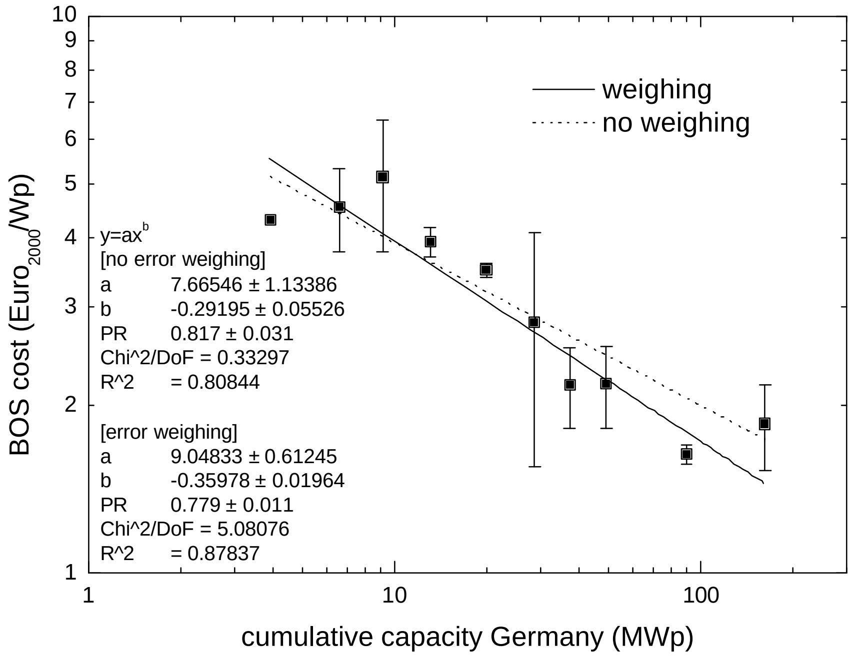

Figure 3.10 *Experience curve for balance of system prices of residential systems in Germany*

Progress ratio for BOS is about 81% over period 1992-2001 in the Netherlands
A similar analysis for residential systems in The Netherlands[4] which gives a PR of 0.81.

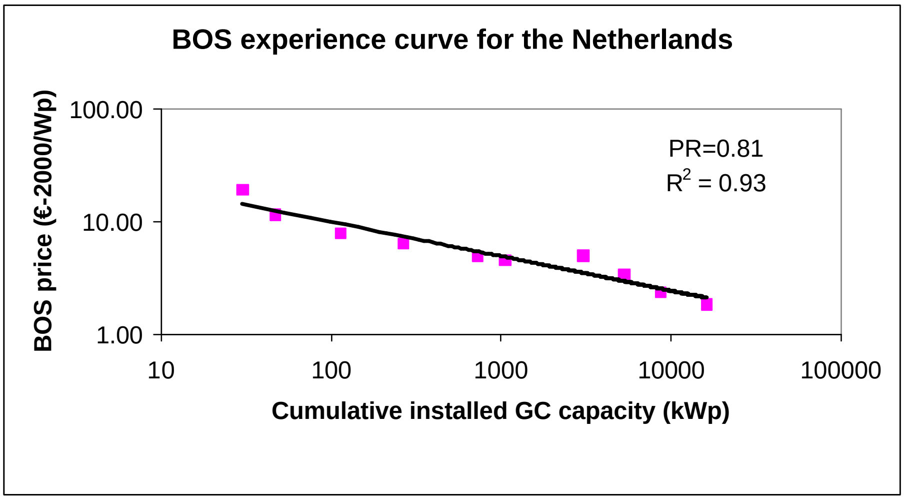

Figure 3.11*Experience curve for balance of system prices of residential systems in the Netherlands*

This result is close to that for Germany. We can conclude that BOS learning in The Netherlands has been comparable with that in the German market, despite the substantial differences in the type of installed systems[5] and in policy approach.

[4] The reliability of these results is less because most records for the Netherlands gave only total system prices and did not include module prices. Therefore we used estimated module prices (based on German prices) in order to derive BOS prices.
[5] Germany: mainly retrofit on existing, individual houses, market stimulation by feed-in tariff;
Netherlands: mainly roof-integrated systems in large new housing projects, market support by technology-oriented learning programme that includes experimental concepts.

For the whole of Europe a BOS experience curve can also be drawn for small and medium size systems (< 100 kWp). This yields a Progress ratio of about 80% too, a result that is not surprising as the price data in the Photex database are dominated by German and Dutch systems.

When we look at the BOS prices of large-scale systems (>100 kW) it is unfortunately not possible to make an experience curve because the price data show too much scatter. A regression for complete system prices[6] also gives a not so good quality of fit (R^2=0.44) but a Progress Ratio which is familiar, namely 0.82. Assuming that modules had a 0.80 Progress Ratio we can conclude safely that BOS for large-scale systems must have had slightly higher PR (ca. 0.84).

3.4.2 Price developments for solar inverters

Progress ratio for inverters is in the range of 91%-96% over period 1995-2002
Also we can take a look at prices for one specific and important BOS component, namely inverters. In Figure 3.11 we show the experience curve for solar inverters in the Netherlands and Germany[7], based on list prices[8] quoted by manufacturers.

[6] We used the total installed capacity of central grid-connected systems in OECD Europe as the x-axis parameter (IEA-PVPS data). The market share of these systems has been more or less constant since 1993 therefore it is allowed to analyse the *compound* system price in this way.

[7] Inverters smaller than 0.5 kW were excluded, because this specific market segment has a slightly higher price which would distort the experience curve analysis. Because it was not possible to obtain sufficient data on historic production volumes from manufacturers, we have used the installed grid-connected PV capacity *within a country* as a proxy for the volume of sold inverters. Our impression is that up to 2000 inverter manufacturers in the Netherlands and Germany sold most of their inverters on their home market. Lately the inverter market seems to widen gradually to an European scale. Therefore we take the boundary of the learning system to be that of the installation country, with the corresponding choice of volume parameter.

[8] Further note that the Y-axis gives the specific price relative to the *nominal inverter capacity*, which in an installed system may be different from PV system capacity

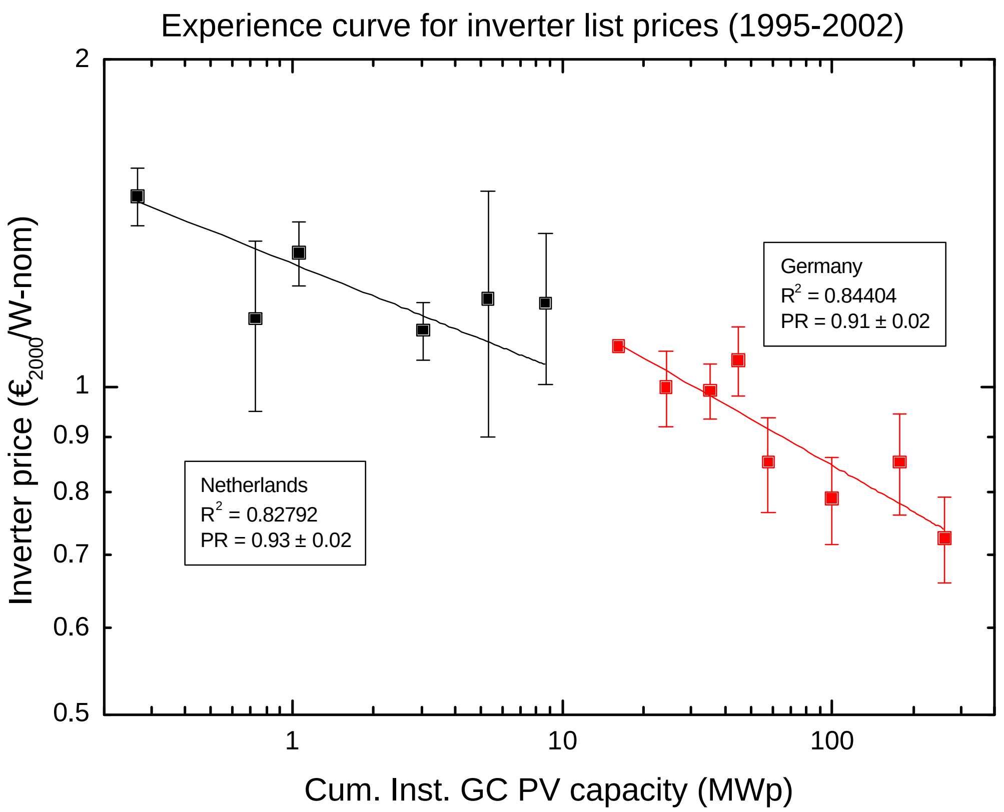

Figure 3.12*Experience curve for inverters in Germany and the Netherlands. Price data were derived from manufacturer catalogues, for the x-axis parameter the cumulative capacity (source IEA) of grid-connected PV systems in each country was used.*

The progress ratio for these inverters appears to be in the range of 0.91 to 0.96 with the German experience curve showing a steeper curve. We have no ready explanation for this difference, one reason might be that Dutch manufacturers had less market growth than the PV installation data suggest.

It is interesting to note that inverters seem to show a less steep experience curve than PV modules, despite the attention to inverter development in national research programs. One reason could be that progress with respect to inverter technology has been focused more on improving their efficiency, reliability and lifetime, al factors which do not show up in the installation price but do help to reduce the life cycle energy cost of the PV system. Reliable data on these aspects were not readily available so that an analysis of this effect is not possible within this study.

Another important aspect may be that solar inverters are part of a broader market of inverters for the recreation market (boats) and UPS[9] systems for computers. This implies that the market development on this broader market should be taken into account for the experience curve analysis. If the market of inverters for UPS applications is substantially bigger than for the solar market, the 90% PR might be an underestimation. When the solar application is going to dominate the inverter market at some point in the future, inverter prices may go down more rapidly.

[9] Uninterruptible Power Supply, consisting of a battery storage and an inverter, used as a back-up power supply for critical loads.

PR's for non-inverter BOS prices have been significantly lower than 80%
One important observation that we can now make is that the relatively high PR for solar inverts implies that learning for BOS prices *excluding inverters* (i.e. array supports, cabling, installation) has been significantly better than for BOS as a whole. A rough estimate based on PR =0.80 for BOS, PR =0.90 for inverters and 30% share of inverters in the BOS price give a PR for *non-inverter BOS* of 0.76. In other words, non-inverter BOS prices have shown a faster rate of price reduction than modules over the considered period. This is quite remarkable because it has often been suggested that BOS components would have less room for price reductions than PV modules. The actual situation has been the opposite however, be it for grid-connected residential systems over a limited time period.

3.5 BOS learning spill-over between countries

We have already discussed that, although the BOS learning system to a large extent can be expected to be national, the speed of learning has not been very much different in (two) different countries (NL and DE). Another interesting point to consider point is whether entrant countries can learn from frontrunner countries.

The following table shows the average system, module and BOS-prices for residential systems in 2002 in four different countries, based on the Photex dataset:

Table 3.1 *Average PV, Module and BOS prices in 2002 in different countries for rooftop systems in the Photex database*

Country	PV-system price (Euro/Wp)	Module prices (Euro/Wp)	BOS-prices (Euro/Wp)
NL	4,83	3,17	1,66
DE	6,42	4,57	1,85
IT	5,25	2,95	2,30
FR	5,28	2,86	2,42

We have to add that the price data for the Netherlands, France and Italy in 2002 are dominated by systems installed in the framework of the so-called HipHip project. This EU-funded project[10] aimed at realizing low-cost, residential systems and had specifically set fairly low price levels, which the suppliers had to meet. For Germany system and module prices in the Photex dataset are considerably higher because no HipHip systems are included for this country.

The table shows that BOS-prices in 2002 were somewhat higher in Italy and France, countries which stepped into the residential market only around 2000. The difference is about 0.5 Euro/Wp, which is more than compensated by the lower module prices in these countries. A few years earlier BOS-prices were above 3 Euro/Wp in all countries. This shows that new countries, although they do lack in BOS-price experience, can start at a lower price level and in that way profit from the learning experiences in other countries. In other words, although the BOS has its specific national aspects, BOS learning can still spill over from one country to another, be it with some delay due to necessary adaptations to the local context.

3.6 Conclusions with respect to PV experience curves

Progress ratio for PV modules has improved from 80% to 77%
We have seen that for module technology, which we consider as a *global learning system*, the progress ratio has been around 0.80 if we consider the full period from 1976 to 2001. However for the last 15 years there seems to be a steeper learning curve with a PR around 0.77 or even lower. Other authors

[10] For more info on the HipHip project see http://www.hiphip.net .

had already reported similar results (e.g. Parente et. al. 2002). From the Photex data it also appears that module prices in Germany have stabilised or even increased somewhat in the period 1999-2001.

BOS-progress ratio comparable to module progress ratio
A new result is that for the Balance-of-System of residential grid-connected PV systems a comparable PR of 0.80 has been realised in both Germany and the Netherlands. We have argued that BOS learning will occur mainly in a national context due to differences in building practices and codes and customer preferences. This assumption has important methodological consequences for the experience curve analysis, which can give rise to erroneous results if ignored.

The sharp BOS price reductions that we observed were not quite as expected beforehand. On the other hand, prices of inverters have shown only moderate reductions and a PR around 0.92. It may well be, however, that the *life cycle cost* of inverters have gone down more steeply because increased performance in terms of efficiency, reliability and life time. The moderate result for inverters implies that learning for non-inverter BOS (support, cabling, installation) has seen an even better Progress Ratio than 0.80.

Learning in BOS can be reached in different ways and can be transferred over country borders
From these results we may conclude that the policy programmes in Germany and The Netherlands, although they employed quite different approaches, both have been very successful in bringing down BOS prices for grid-connected residential PV systems (see also Chapter 4).

Finally we have shown that countries can learn from each other with respect to BOS development. In other words, although the BOS has its specific national aspects, BOS learning can still spill over from one country to another, be it with some delay due to necessary adaptations to the local context.

4. PRICE DEVELOPMENTS AND POLICY PROGRAMS

4.1 How are price developments related to policy programs?

The question that will be dealt with in this chapter is how price developments in PV-systems and components can be related to specific policy programs in various countries. In order to tackle this question we have studied the policy programs of four countries in the period 1990-2002: Germany, The Netherlands, Italy and France. We have tried to relate the programs to the observed price trends and experience curves for PV systems and PV components on the basis of the Photex database and as partially presented in Chapter 3. Although the analysis was intricate and our findings difficult to interpret due to the lack of a sufficiently long historical range of reliable data, we have drawn some conclusions anyway. These conclusions we present in this chapter.

Section 4.2 will give a short historical overview of the programs in the four countries mentioned. In section 4.3 we will present the main conclusions from analysing our data set.

4.2 Policy programs and price trends in NL, D, I and F in their international context

4.2.1 International context

For any given place in Europe, four levels of energy policies apply that can influence the development of photovoltaics:

- International level
- European level
- National level
- Local level

The funding resulting from these different policies are sometimes used in combination with European support (cf. Hip-Hip or PV-Salsa…). Therefore, for particular projects, the parallel is made between the funding and their origin and the impact on the system price in one given country.

As a second remark, we point out that different countries have different regional strategies. For example, while Germany pushed the grid-connected PV applications from 1991 onwards, at the same time France pushed stand-alone application more and financed a lot of research on storage for PV because of a different geographical and political background.

Finally, a technological breakthrough allowed by the R&D funding in one country will impact the worldwide market. Especially for what concerns the module price that is set at a worldwide level, this effect is extremely high.

All these factors contribute to the fact that the number of parameters is extremely high and their interdependence also, so that all analyses about experience curves and their relations to policy should be put in balance with the uncertainties (and hence robustness) in the conclusions.

Kyoto

Renewable energy policies in Europe are inserted in a worldwide context with in first line the commitments made in the Kyoto Protocol in 1997, where the developed countries agreed a legally-binding commitment to reduce greenhouse gas emissions by 5.2 per cent below 1990 levels over the period 2008-2012. In the meantime, the United Nations Framework Convention on Climate Change (UNFCC) takes a look at the evolution of the measures in the committed countries and publishes the national communications on policies and measures. The hierarchy of the European and National policies is presented in Figure 4.1.

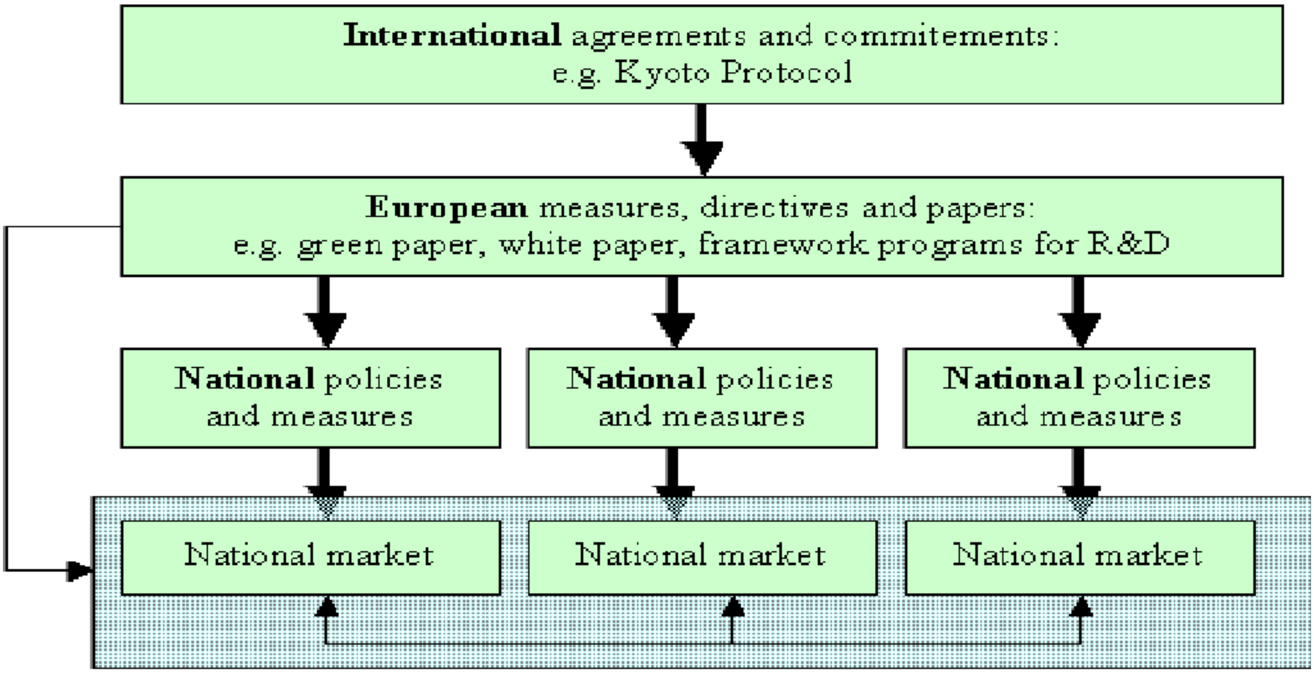

Figure 4.1 *Hierarchy of national and European policies*

The Kyoto protocol is a strong driving force for the development of clean technologies for electrical energy production.

European market deployment policy
European papers and directives that affect the development of PV technology and its deployment are listed below:

- Common rules for the internal market in electricity, Official Journal, L 27, 30.01.1997
- EU White Paper on Renewable Energy Sources, of the 26/11/97
- Green paper: Towards a European strategy for the security of energy supply 29/11/2000
- EC directive on green electricity adopted in September 2001

Of these 4 documents the last one is the most closely related to PV policy programs. In the directive the following items are important:

- The Member States are supposed to publish, by 27 October 2002 at the latest, and every five years subsequently, a report setting the indicative Member State targets for future RES-E consumption for the following ten years and showing what measures have or are to be taken to meet those targets.
- The Member State targets must take account of the reference values set out in the Annex to the Directive for Member States' indicative targets concerning the share of electricity produced from renewable energy sources in gross electricity consumption in 2010.
- They must also be compatible with all the national commitments entered into as part of the commitments accepted by the Community at Kyoto.
- Member States are required to publish on 27 October 2003, and every two years subsequently, a report which includes an analysis of success in meeting the national targets. The report should also indicate what climactic factors are likely to affect meeting the targets and to what extent the measures taken are consistent with national commitments regarding climate change.
- At Community level, the Commission will publish a biannual report, the first on 27 October 2004, based on the national reports assessing the extent to which:

- the Member States have progressed towards achieving the national targets;
- the national indicative targets are compatible with the global indicative target of 12% of gross domestic energy consumption in 2010, and in particular with the indicative share of 22.1% of electricity from renewable energy sources out of the total electricity consumption of the Community in 2010.
- Should the Commission's report conclude that the national targets are liable to be inconsistent with the main objectives of the Directive, the Commission may present proposals to the European Parliament and to the Council with respect to the targets, including, if need be, proposals for obligatory targets.

- The Commission will present, by 27 October 2005 at the latest, a report on the experience gained concerning the application and coexistence of the different support schemes in the Member States. This report will evaluate the success, including the cost-effectiveness ratio, of the support schemes for the promotion of RES-E consumption. This report will be accompanied, if necessary, by a proposal for a Community framework for support schemes for RES-E

These policies, papers and other directives lead to unavoidable transformation in the different European countries. The national policies are for a large part a result of these European constraints.

In parallel to the regulatory role of the European Community that obliges the member state to undertake actions in favour of PV deployment, the different European programs for R&D were funding numerous projects related to PV.

4.2.2 The Netherlands

Netherlands: general context[11]

In the Netherlands, PV was originally mainly off-grid until 1995 (Figure 4.2). Only 1998 or 1999 did the amount of installed grid-connected PV pass the amount of installed off-grid PV.

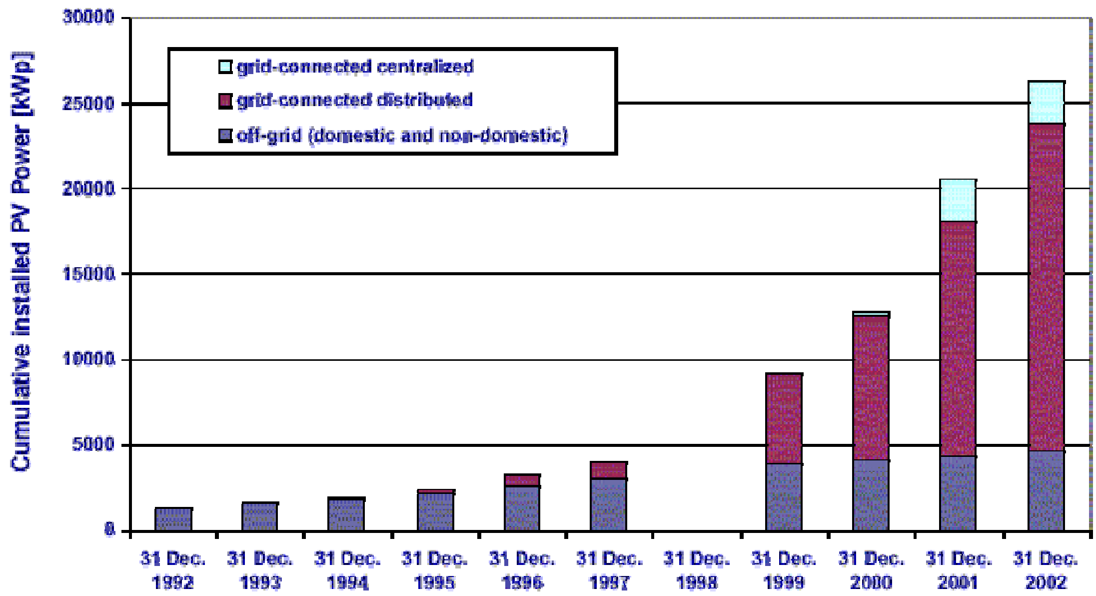

Figure 4.2 *Installed capacity in the Netherlands*

Government Support for PV technology in the Netherlands

R&D

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[11] Most information has been based on a document that is to be published shortly (De Vries et al., 2003). R&D budgets have been mentioned in (Gerwig, 2003).

Before 1990 cell research received the most attention. After 1990 this gradually changed, research shifted from mainly cells to cells and systems. In Figure 4.3 the budgets of the different R&D programs on PV are shown.

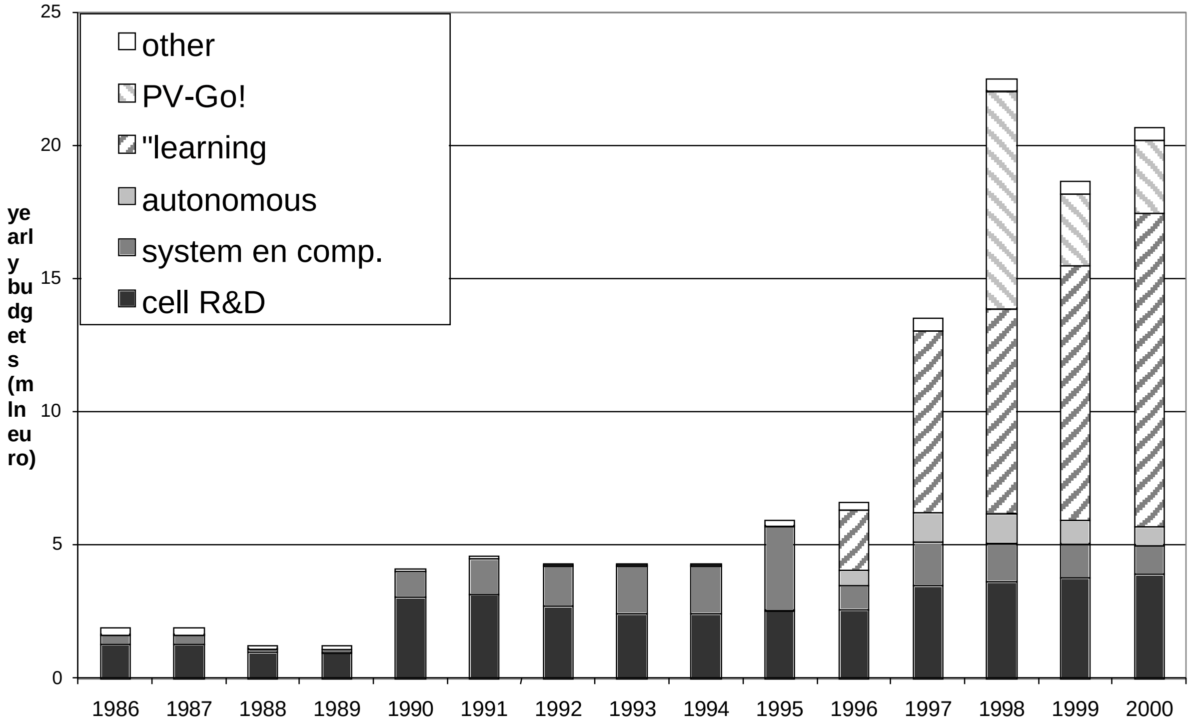


Figure 4.3 *PV budgets in the Netherlands in million € [Van Mierlo, 2002]*

After 1995 next to the cell and system research, dedicated budgets for grid-connected applications ("Learning Programme PV in the build environment" and "PV-GO") were added. The Learning Programme was set up to stimulate innovative pilot projects for large-scale applications, while PV-GO was a tendering scheme for small systems. Note that in the figure the view on budgets for demo projects is somewhat distorted because before 1995 these projects fell into the category "system and component R&D".

Market support
The market support mechanisms for PV have been various and have changed quite a few times during the last 10 years.

In 1995 there are three financial arrangements. The tax exemption for the Regulatory Energy Tax (REB), the support from the Learning Program and the Arrangement Green Projects.

The REB or Regulatory Energy Tax aims to reduce the energy use of companies and households. It comprises a tax on the use of energy. However, electricity produced by renewable energy sources is exempted so that is effectively a subsidy on renewable energy generation. Table 4.1 lists the height of the tax exemption for the period 1999-2003.

In 2003 however the tax exemption of renewables was reduced and replaced by a different subsidy scheme (a direct subsidy called the MEP). During 2004 the REB arrangement will be replaced completely by the MEP, which will provide a 9.7 €ct/kWh incentive for solar electricity.

Table 4.1 *The level of the tax exemption from the Regulatory Energy Tax for renewable electricity (VAT included).*

	1999	2000	2001	2002	2003
Tax exemption (€ct/kWh)	2.6	4.4	6.9	7.1	3.45

The learning program arrangement aimed to stimulate the use of sustainable energy and environmental energy technologies by providing subsidy for RD&D projects in the field of renewable energy. The percentages of project costs covered are dependent on the type of project.

The Arrangement Green Projects consists of a Green Investment Funds for individual persons and companies. The goal of this program is to stimulate investments in environmentally friendly projects. by means of a tax exemption of the interest gained on the investments in the Green Funds.

In 1997 these three arrangement were extended with the VAMIL (Free depreciation choice for environmentally friendly technologies) and the EIA (regulation that investments in sustainable energy equipment can be deducted from taxable profit under certain conditions). The EIA, VAMIL and the Arrangement Green Projects could be combined.

In 2001 another support scheme was introduced: PV became a technology that could get a subsidy under the Energy Performance Regulation (EPR). This regulation is primarily meant for electric household appliances, like energy efficient dryers, freezers, cooling units etc. The EPR financing scheme was also introduced for PV. The EPR is meant for house owners and house tenants. After installation of PV the government refunded 3.50 € per Wp. When the EPR is combined with an Energy Performance Advice (EPA), which is an advice of energy saving measures by an expert, the EPR for PV is raised with 25%. In 2003 this percentage was lowered to 10%.

Next to these subsidy schemes it is not uncommon that energy utilities and municipalities give additional support. Traditional energy utilities have built up funds during the period before liberalisation for environmental investments (Environmental Action Plan funds, better known as MAP-funds) until the year 2000. Not all of these funds have been spent before the end of the year 2000. The remainder have been spent, among other things on PV, in the years thereafter.

Analysis for the Netherlands

Many different market support measures, boom and bust

The of the case of the Netherlands shows a very large variety of measures of which many are/were acting at the same time. As can be seen from Table 4.2, over 10 kinds of tools were available in the Netherlands in 2000 for PV support. For a private consumer in 2000, the incentives that could be applied for were EIA (fiscal measure of tax exemption), EINP (subsidy for investment), PV-GO (investment subsidy for special PV systems), EPA-EPR that are information and investment support and tariff from the energy levy. This number of measures is not acting in favour of a clear view for the customer and leads to an administrative burden that can be heavy to carry.

Table 4.2 *Policies for PV in the Netherlands*

Programme	Operating principle	Year of implementation	Financial	MWp installed
NL - MAP	voluntary agreement between energy sector and ministry of economic affairs, objective 3.2% of the electricity distributed from renewable sources by f 2000. Utilities designed and implemented their own programmes, financed by a so-called 'MAP	1990 – 2000. Remainder of MAP funds have been spent after 2000 until 2003		

	levy' (on average 1.8%) on energy consumption			
NL - VAMIL	allows investors in environmental technologies (defined explicitly by a VAMIL-list) to freely offset their investments against taxable profits, resulting for the investor in an interest benefit. The VAMIL is especially interesting for entrepreneurs with high profits (higher tax scale). The advantage of VAMIL is at the beginning of a project, as taxes will increase during operation.	1991 - 2002		
NL – NOZ-PV	PV covenant: objectives 7.7 MWp in 2000, 500 MWp in 2010 (a new (and not ratified) PV covenant was projected that aimed at a target of 300 MW by 2010 and 1400 MW by 2020)	1994 - ongoing		
NL- BSE-NOZ	This “Learning Programme” was set up to stimulate innovative pilot projects for large-scale applications. The BSE arrangement aims to stimulate the use of sustainable energy and environmental energy technologies by providing subsidy for RD&D projects in the field of renewable energy. Every year a certain amount of money is made available for the BSE. The percentages of project costs covered are dependent on the type of project.	1994-1998 (later PV-GO)		
NL- REB	energy levy on electricity and gas consumption by small and medium-size customers. Energy from renewable sources is exempt for the tax. The proceeds from the tax can be used by suppliers as a premium tariff for renewable energy producers (not mandatory). In 2002 this combination added up to 8.0 €ct/kWh (6.0 €ct/kWh tax exemption + 2.0 €ct/kWh production support). Since 2001, a Green certificate System for the validation and monitoring of the production and sales of green electricity under the REB. Will be adapted in 2003: lower exemption level of taxation (2,9€ct/kWh for PV) on consumption + technology specific feed-in tariff (MEP).	1997 - ongoing		
NL – EIA	fiscal measure: investment to be deducted from taxable profit up to 55% of investment costs (= up to 19 % of investment costs) maximum deduction € 99 million per fiscal entity. minimum investment (in the year of application) € 1900.	1997 ongoing		
NL – EINP	subsidy for stimulation of investment in renewable energy: 18,5% of investment for not-for profit organisations and 20%	1997 -ongoing		

	for individual persons. (ECN 2003) for investments larger than € 1750.			
NL – PV-GO	rebate programme for specific grid-connected PV applications with sufficient marketing potential. (up to 25% of the system costs).	1998		900 kWp in 2000
NL – MEP	Feed in tariff (expected to be 6.8 €ct/kWh) guaranteed for a maximum of 10 years. The subsidy is to be financed by a levy on all connections to the electricity grid in the Netherlands. The MEP producer support will exist next to REB exemption for specific RE technologies (see above).	July 2003	0,068 €/kWh 0,097 €/kWh after 1 July 2004	
NL – EPA, EPR,	information and Investment support	2000	3.5 Euro/Wp	
NL - green labels	Objective: to distribute the cost burden of the renewable electricity target.	1998 – 2000 (Part of MAP)	about 0.023 €cents/kWh	
NL - green funds	Soft loans (1%) for "green projects" induced by tax exemption on interest from Green Funds			

On the one hand all these different measures made it very complex to get the subsidies an investor in PV could get. On the other hand, after a while professional organisations designed financial arrangements, sometimes for special customer groups (e.g. for 'companies' with their 'shop' at home, such as general practitioners and other people in the care sector) that combined the maximum of the instruments, in such an intelligent way that the costs of PV-systems were almost completely covered. The market boomed in 2003 (about 22 MWp) installed, but during 2003 the government decided to abolish the main support i.e. the one from the EPR from 2004.

Due to all these subsidy regime changes the market in the Netherlands shows cycles of bust and boom, which is giving much insecurity on the Dutch market.

R&D-effect difficult to recognise at national level
Figure 4.4 shows the capacity installed in the Netherlands together with the overall funding. Apparently cell R&D funding had no noticeable direct impact on the market deployment. That corresponds to the idea that cell R&D takes place in an international setting and has no direct local effects. Also the effects of fundamental R&D come later and are part of the long-term experience curve.

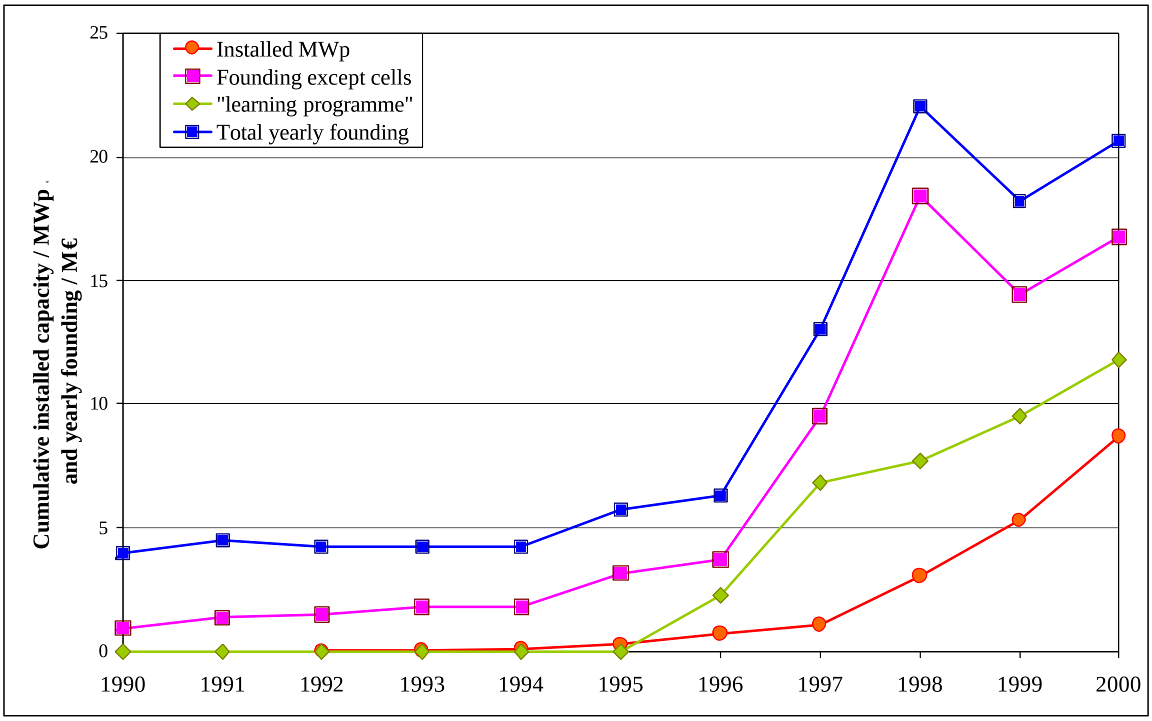


Figure 4.4 *Installed capacity in the Netherlands and funding*

The market took off with the creation of the learning programme in 1995 but was even more impacted by the PV-GO ('learning') programme that contributed to the huge market increase of 1998.

Figure 4.5 shows to which extent the installation of PV is relying on the national funding. The origin is 0€ funding in 1986.

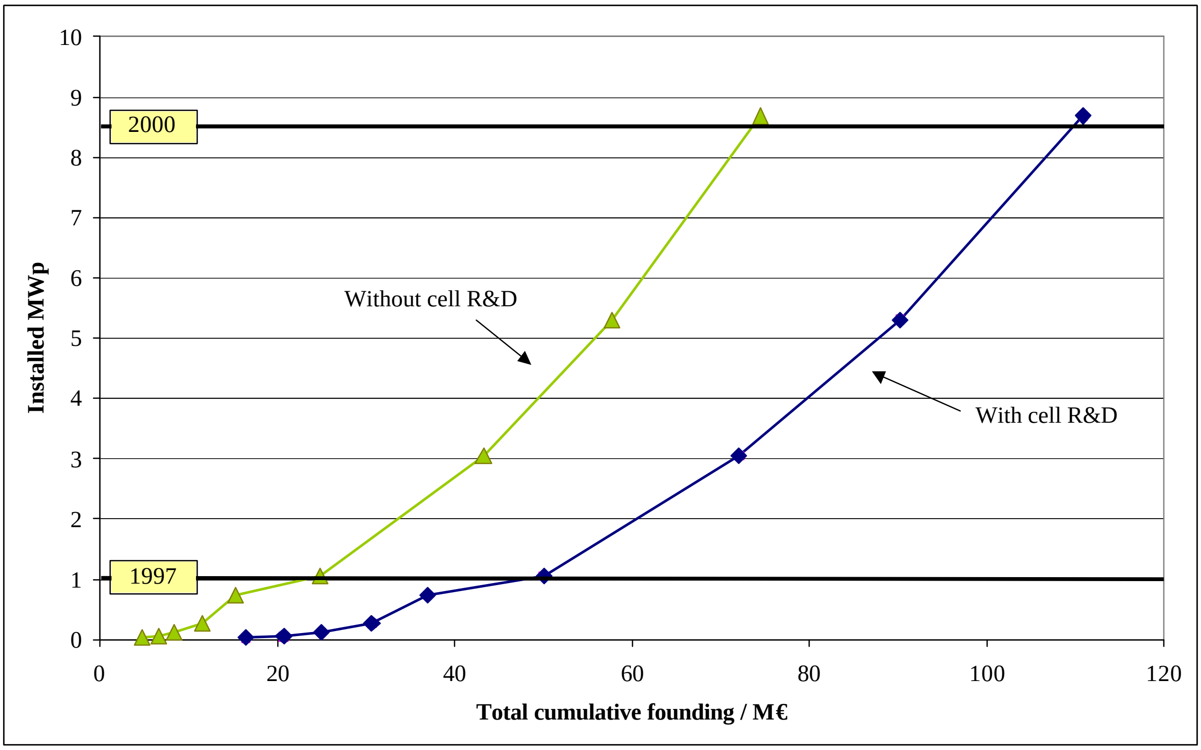


Figure 4.5 *Total installed capacity over cumulative national funding in the Netherlands with and without cell R&D*

Market support covers system cost

In the first part of the curve, the increase in funding had only very little impact on installed capacity (years 1992 to 1997). Between 1998 and 2000, the growth of installed capacity depends in a more or less linear way on the increase of cumulative funding. The market development is directly proportional to the funding with a national funding in the range of 6.5 M€ for each new MWp installed if one excepts cell R&D. These are the implementation years of PV-Go and in first line of the learning program for which the budget increased in the quoted years.

BOS-prices reduced by learning program

Figure 4.6 shows the parallel between PV system price and the national budgets for PV. A delayed correlation in the end of the curve seems to appear with a strong lowering of the system price (from 1998 on) that is related only partly to a decrease in the module price. This decrease in the BOS price is possibly related to the effort made in the range of "learning programmes" (including PV-Go) that began in 1996 and continued in the next years.

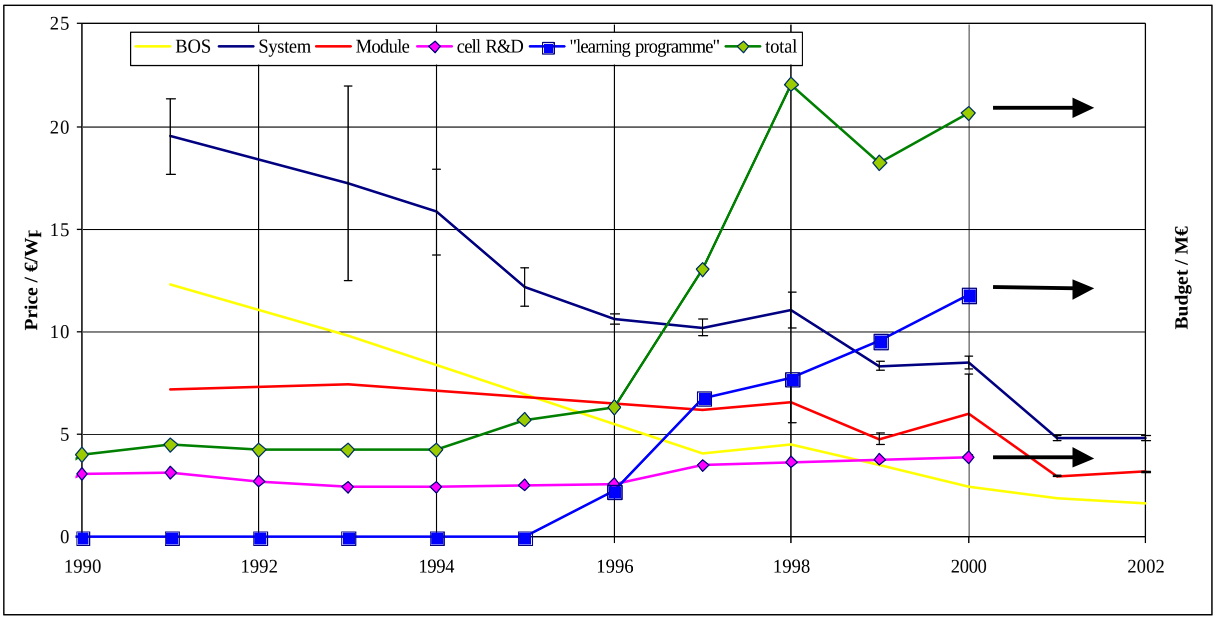


Figure 4.6 *System price and PV budgets in the Netherlands*

Sudden increase in support temporarily leads to higher module prices

As a matter of fact, for the two years where a strong peak appears in the national funding, an increase of the price of the system can be observed (1998 and 2000). The peaks in funding are related to budgets for the PV-GO programme. In both cases the average module prices in the Netherlands increased.

4.2.3 Germany

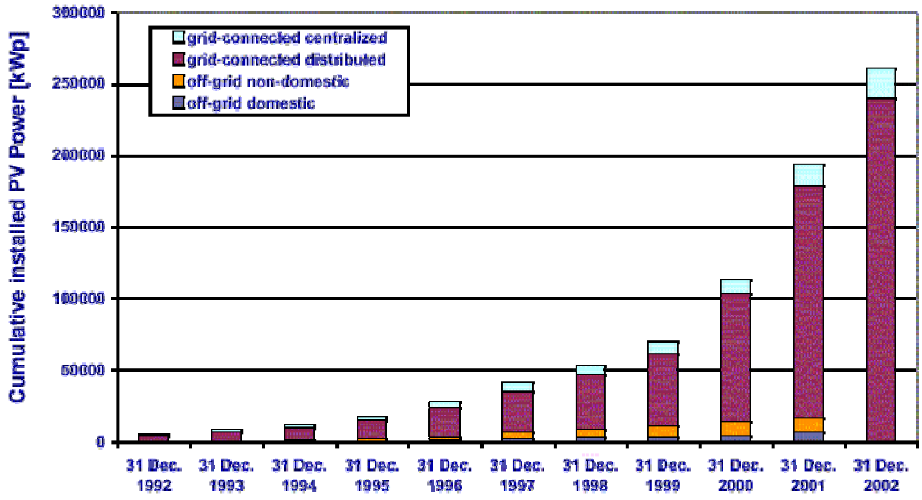


Figure 4.7 *Installed power in Germany (Source IEA)*

General context

In Germany, strong emphasis was given to the deployment of grid-connected PV from 1991 on and the part of installed power dedicated to other uses is becoming almost negligible, in particular stand alone applications. Installation of off-grid systems did not take place at all until 1995 and constituted after 1995 only a very little part of the installations. Germany is the European country with the largest installed PV production capacity.

Table 4.3 *National programme data collection Germany*[12]

Programme	Operating principle	Year of implementation	Budget (M€)	MWp installed
1.000-roofs	Investment subsidy of 70% of costs with upper price cap.	1991 / 1995	Estimated 50% of R&D budget of 103 M€	2012 systems with 5.3 MWp
Different subsidies of federal states	first only inv. subsidies latter years partly soft-loans	1991 / ongoing	163.67 M€	Budget oriented limit not MW installed
Electricitiy-Feed-in-Law	Feed-in-tariffs *(90% of average price for end consumer)*	1991 / 31.03.2000	3.5 M€ (paid by final customers)	Not separately defined – see market development (table 2.7)
Cost covering feed-in tariffs from utilities and local communities	Feed-in-tariffs of up to 1.12 €/kWh fixed for 20 years	1996 / 1999	Cap of allowed electricity price increase 1-3% fixed by price regulatory authority	8 MW in 1996 and 1997
Green tariffs from utilities as voluntary participation for the customers	A) higher feed –in-tariff paid to realise new PV plants B) single subsidy by customers for fund investing in PV	1996 / 1999	A) Only RWE as largest utility had 10 000 customers (of 3 M) paying plus 0.1 €/kWh B) PV at school (see below)	Approx. 1 MW
Sponsoring from utilities partly with voluntary participation for the customers	Investment subsidy for PV at schools	1996 / 1999	700 schools	Approx. 0.8 MW
Market stimulation programme	Invest. Subsidy to PV on schools	1999 / ongoing	Subsidy of 0.76 M€ in-duced 4.93 M€ total investments	252 projects!
Market stimulation programme by federal foundation DBU	Invest. Subsidy to PV on churches and congregations	1999 / 2001	Subsidy of 13 M€ for PV and solarthermal	700 projects of which 622 are PV plants with a total of 2.68 MW
100,000-roofs	Soft loan: 10 years duration, 2 years free of redemption	1999 / Ongoing	Subsidy of 695 M€ (approved) induced 1.56 billion € investments	126 (table 2.10)
Renewable Energy Act	Feed-in-tariff of 0.457_{2002} fixed for 20 years (5% decrease annually for later installation from 2002 on)	01.04.2000 / (ongoing)	83 M€ (paid by final customers)	Not separately defined – see market development

[12] All data displayed in this section are derived from Jahrbuch erneuerbare Energien from Fritjof STAISS

Analysis for Germany

Clear form of (large) market support

A first point that differs from the case of Netherlands is that only few concomitant measures can be observed in Germany. This made it very clear to the actors how to get subsidies for their systems. The market in Germany has become the largest in the world after Japan.

Figure 4.8 shows the annual evolution of the installed capacity and of the national funding (includes both cell research and feed in money).

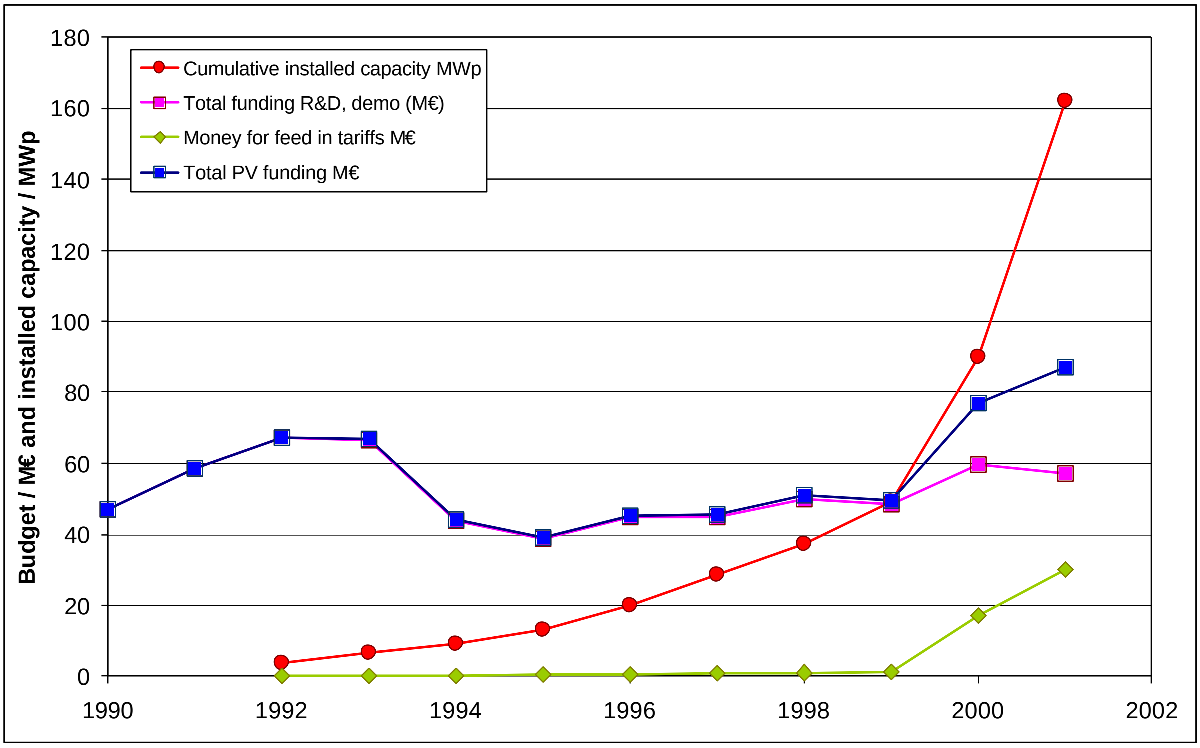


Figure 4.8 *Cumulative installed capacity and annual funding in Germany*

There was a clear peak in funding in the years 1992-1993. In this year, the existing measures for PV were the 1000 roofs programme, funding from different national subsidies and the beginning of the feed in tariffs. The high level of funding did not impact much the market.

A very noticeable rupture is observed in the curve in 1999 that corresponds to the market support programme beginning with soft loans and secured feed in tariffs. Clearly, the contribution of the feed-in tariffs to the PV funding was marginal until 1999.

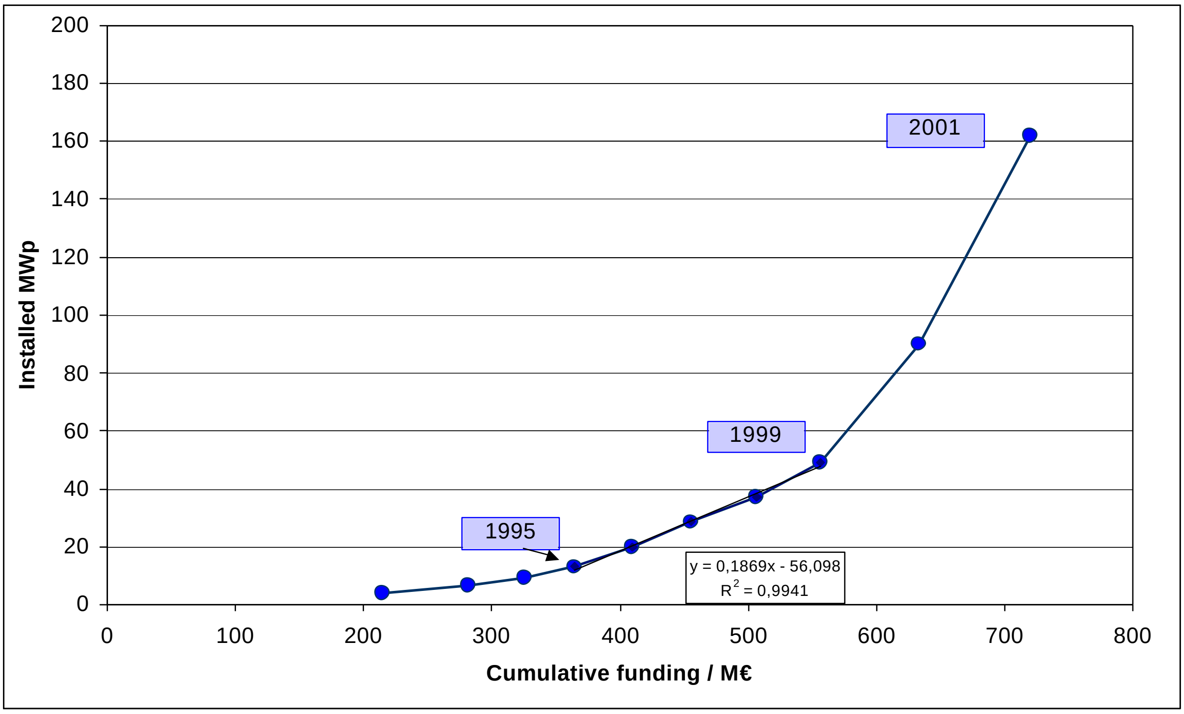


Figure 4.9 *Cumulative installed capacity over total cumulative national funding in Germany*

System costs covered by support and incentive schemes
Until 1995, the amount of funding for each MWp installed does not decrease much. Between 1995 an 1999, the dependency is linear with a funding in the range of 5.3 M€ for each new MWp installed. Between 1999 and 2000, the value decreases to 1.88 M€ for each new MWp and to 1.21 M€ the year. Since the REA (renewable energy act) came in force, the PV systems have a secured feed in tariff for 20 years plus the year of installation. As a result, the annual new commitment that is accepted for one new installed kWp is = new capacity (in kWp)*800 kWh/kWp*(current feed- in tariff)(€/kWh)*20 years (assuming an average production of 800 kWh per KWp) minus inflation. For example, for 2002 this leads to an estimated new commitment of some 490 M€ over 20 years, assuming an inflation rate of 3%. For comparison with other policies in other countries where the funding is an investment subsidy, the expense of the commitment should be taken into account even if this funding is no government funding, it is a commitment that is paid by the end user. This means that the support and incentive level in Germany and the Netherlands per MW have been of a comparable level.

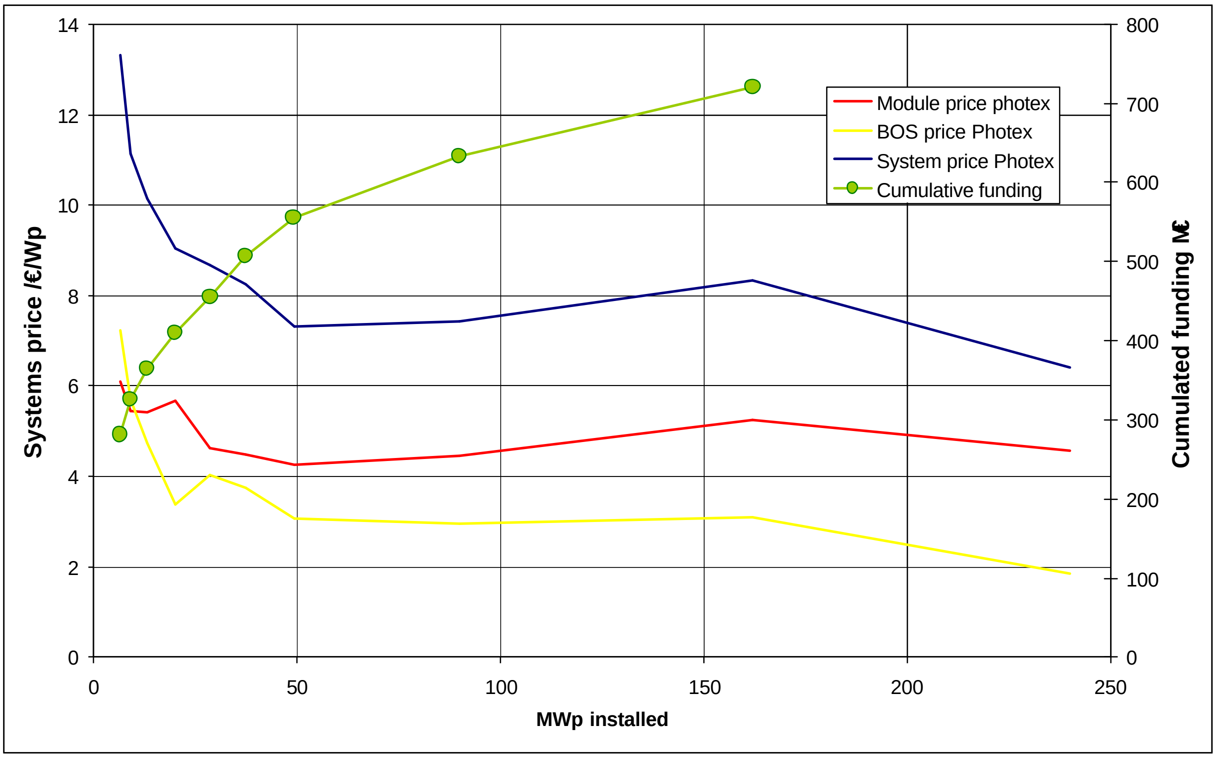


Figure 4.10 *Total cumulated funding and average system price over cumulated installed power from 1993 to 2002*

Temporary higher module prices and strong reduction of BOS prices.

In Figure 4.10, a superimposition of the average system price and the cumulative total funding (excluding feed-in from REA) over the cumulated installed PV capacity from 1993 to 2002 is presented. In this case, the correlation between funding and system price is similar as in the Netherlands: a sudden market demand increase temporarily leads to higher module prices and has after a few years a strong impact on lowering BOS-prices. The dramatic reduction in BOS-prices is also shown by Table 4.4.

Table 4.4 *Investment per kWp without VAT for residential systems (1999/2002) (Source: Fraunhofer Gesellschaft für Solare Energiesysteme)*

System size	**1 kWp**		**5 kWp**		**2 kWp**		**3 kWp**	**5 kWp**	**50 kWp**
year	1999		1999		2002		2002	2002	2002
	Euro	%	Euro	%	Euro	%	%	%	%
modules	4000	48	3800	56	4100	68	> 70		
inverter	1100	13	900	13	650	11			
mounting structure, installation material	1400	17	1100	16	500	8			
installation labour	1270	15	780	11	650	11			
planning, documentation	500	6	250	4	100	2			
Total [Euro/kWp]	**8270**		**6830**		**6000**		**5800**	**5500**	**< 5000**

An elaboration of this table and the possibilities for further cost reduction will be presented in Chapter 5.2.3.

4.2.4 Description of the French situation

General context

France is a country with overseas departments, mainly islands in the Pacific. As a consequence of this geographical particularity, emphasis was given in France more on off-grid electrification than to grid-connected PV in the last ten years; The grid-connected PV took off slowly in 1992 in France but still only has a small share of total installed PV power even if its share of the yearly installed power is growing quickly (see Figure 1.1).

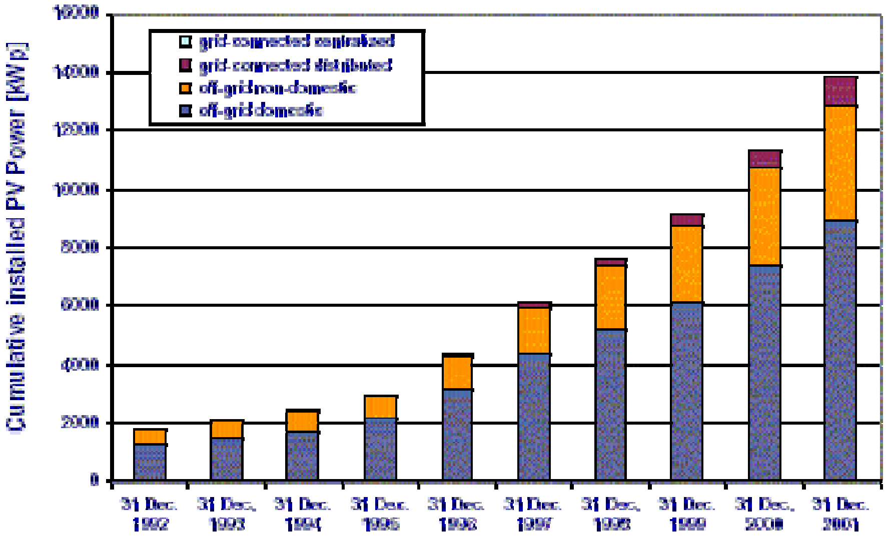


Figure 4.11*Cumulative installed power in France (Source: IEA-PVPS)*

French funding for PV

Currently, the PV R&D in France is financed for a big part by ADEME directly. This national agency was created at the end of 1990. Financial contributions from 2 other public laboratories (CNRS and CEA) complement to an equal amount the ADEME's R&D budget. The incentives for PV installations are supported in France on a national level by ADEME or the French utility EDF with eventually contributions of local authorities. Other small projects can be financed on a more regional basis but these disseminated actions are not reported in this document.

Table 4.5 *French budgets for PV (€ 2000)*

Year	Total funding	R&D National In M€	Demo National + market In M€
1986		11.77	
1987		6.59	
1988		6.01	
1989		8.63	
1990		7.5	
1991		7.44	
1992		7.62	
1993		7.62	
1994		6.68	
1995		6.71	
1996			
1997			
1998			
1999	15.37	7.17	8.2
2000	17.46	8.44	9.02
2001	17.2	9.11	8.09
2002	17.97	9.52	8.45

Off-grid PV systems in France

Most installed off-grid domestic systems in France were funded through a program called "FACE". The costs for off-grid domestic systems is calculated using data from the FACE program.

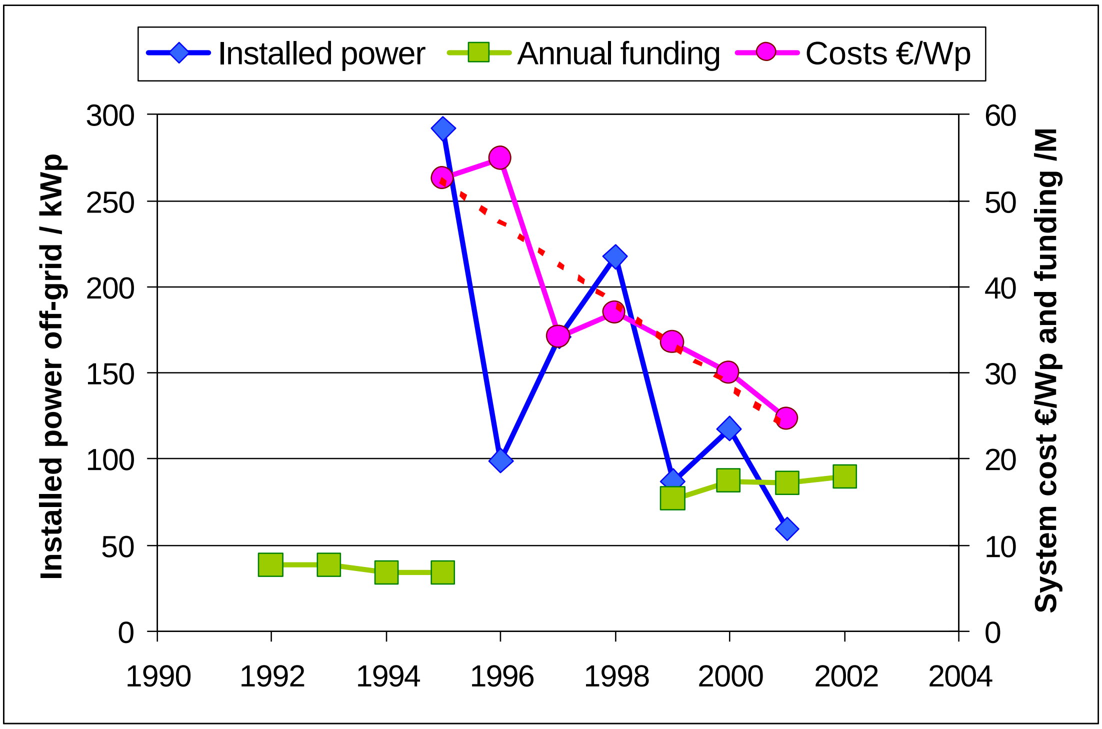


Figure 4.12 *Average systems price for off-grid applications and installed power*

The general trend of decreasing installed power within FACE is related to the fact that the number of existing sites that can potentially benefit from this program is decreasing since the program is meant at avoiding the installation of grid extension. From Figure 4.12 one can deduce that the average system price for off-grid system installation is benefiting a lot from the R&D funding and especially from its progressive increase. In off-grid systems, the price for electricity storage is responsible for a big part of the total price. Since funding R&D for storage is more aiming at increasing the life of the storage system than its installation price, the effects of R&D national programs on the experience curve cannot be illustrated. As a matter of fact, the experience curves in this study are designed for the only installation price and not the delivered kWh.

Funding of Grid-connected PV capacity

From 1993 to 1998, no French public funding was granted to grid-connected PV installations. The grid-connected systems that were placed, were supported by the European Commission programs.

In 1993, HESPUL, a non-profit organisation promoting energy efficiency and renewable energy, began the Phebus programs with a 35% funding of the European community. About 250 kW has been installed under this program.

From 1999 on to the beginning of the French National Program in 2002, grid connected PV installations were financed on a basis of European projects to which ADEME participated for 15% and the regions for another 15%, with the rest being supported by the owner. The projects were the last phase of Phoebus 97, PV-Salsa, HIP-HIP, Universol and PV-starlet. For these projects, the EU contributed 35%, Ademe 15%, regional authorities also 15% and the remainder (35%) by the user of the system.

Since 2002 photovoltaic systems are subject to two types of support granted by the ADEME:

- for support of selected projects within the framework of European tenders restricted to 4,6 EUR per watt (basic grid-connected PV system) and 6,1 EUR per watt (grid-connected system with safety storage)
- or within the framework of a subsidy, in the absence of European Commission financing on tenders, equals to 4,6 EUR per watt which could be increased to 6,1 EUR per watt in the case of a grid-connected PV system with safety storage. These levels should be taken as all public subsidies included. In mainland France, these aid rates will decrease as of 1 January 2005, at 3,8 EUR per watt (basic grid-connected) and 4,9 EUR per watt in the case of a grid-connected PV system with safety storage. A power ceiling was applied, that is to say 5 kW for individuals and 30 kW in the community/tertiary sector, beyond these ceilings, a case-by-case analysis will be carried out. The specifications established by the ADEME determined the design, size and installation rules, as well as the safety rules and the technical measures for integration into the building to be taken into account.

In any case, for the overseas departments, these aids were granted, in the competitive sector, within the limits of the aid rate admitted by the local authorities calculated on the basis of the accepted costs and raised by 10 % for the SMEs.

In addition France introduced a feed-in system: 15.25 euro cents in continental France and 30.50 euro cents in France's overseas departments and in Corsica (lowered by 5% as from 1st January 2003, corrected for inflation). It was not possible to sell any kWh at this price since the purchase contracts became effective mid-February 2003. The solar systems connected to the national power grid still functioned on the basis of a purchase price equivalent to the price paid by the private user, i.e. approximately 9 euro cents per kWh.

Table 4.6 *EC and national funding for grid-connected PV installations in France*

	Installed [kWp]	Cumulative [kWp]	Average specific system price (Euro/Watt)	National budget for grid-connected PV [kEuro]	Contribution EC [kEuro]	Total national budget for PV [MEuro]
1993	0	1			16	7,62 6,68
1994	26	27			48	6.71
1995	13	40			48	
1996	54	94			56	
1997	36	130			216	
1998	69	199			216	
1999	150	349	6,95	469	365	15,37
2000	259	608	5,84	680	529	17,46
2001	364	972	5,67	928	722	17,20
2002	500	1472	5,51	1239	964	17,97

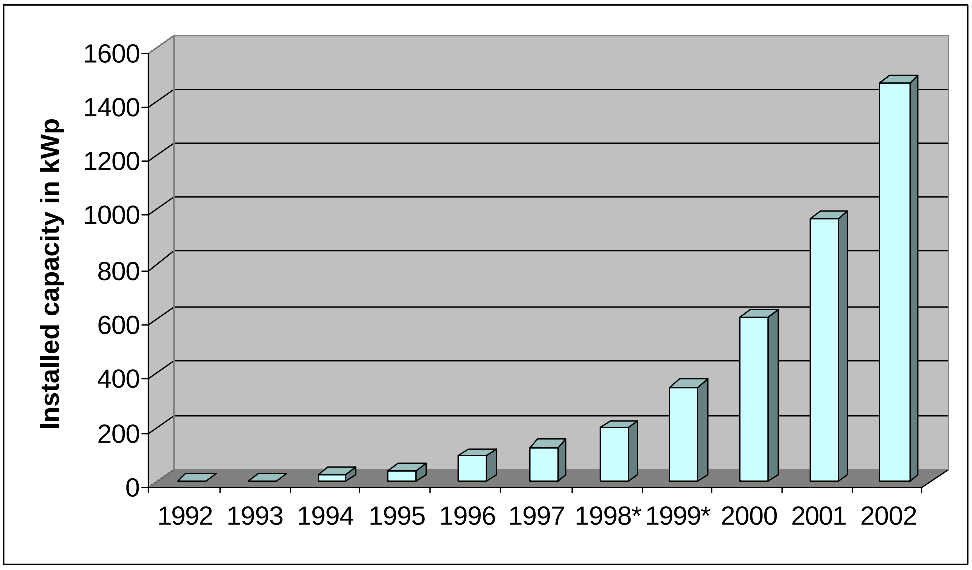


Figure 4.13*Evolution of grid-connected PV in France*

As stated formerly the deployment of grid-connected PV has not been pushed in France. As shown in Figure 4.13, the installation of the first grid-connected PV kWp in France goes back to 1992. All systems installed until 2002 were installed in the frame of European projects. The price evolution curve and the learning curve can only be deduced for the last three years for which data about the system price exist and are picked from the Hip-Hip project.

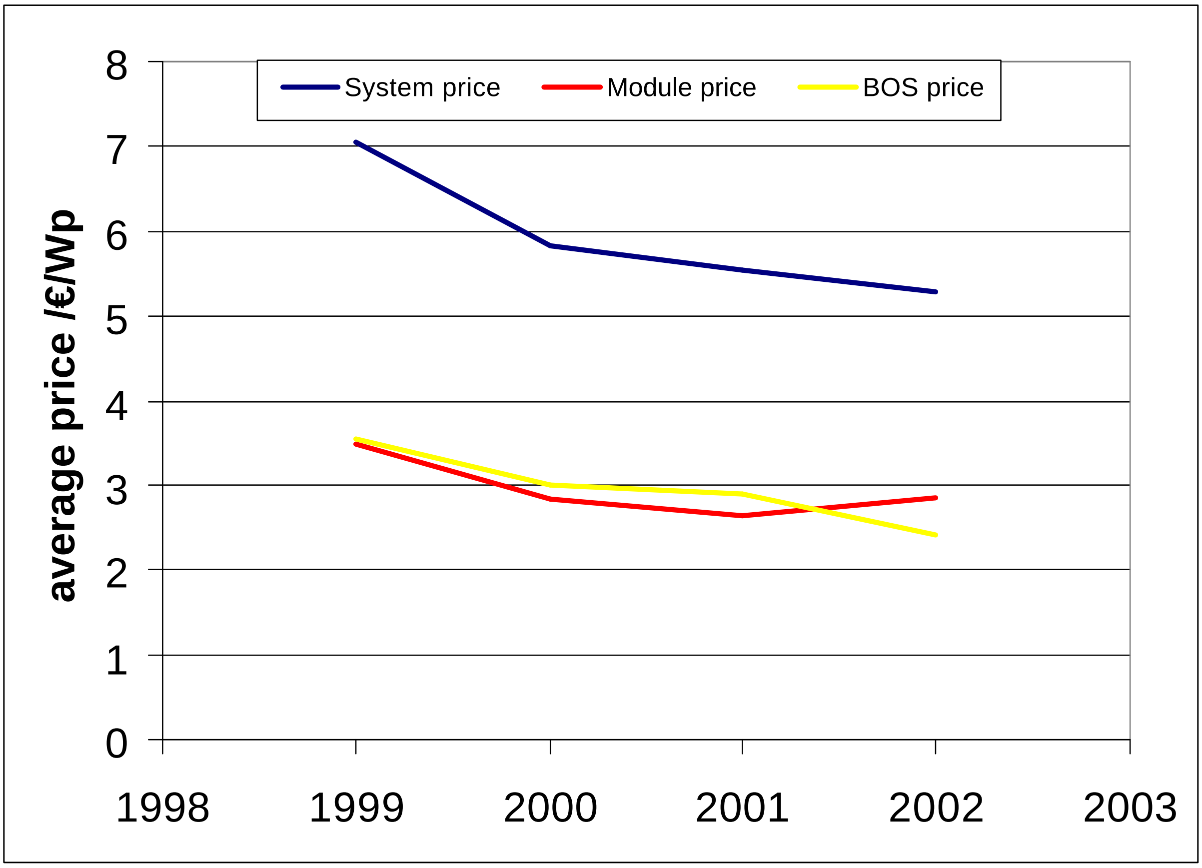


Figure 4.14*Price evolution curve for grid-connected PV in France*

The effect of the feed in tariffs in France cannot be evaluated since until 2003, no purchase contract came into action. In fact, only the effect of the ADEME and regional funding can be evaluated and they are occurring as a support to EC demonstration projects. In conclusion, there is no real self carrying grid-connected PV market in France yet. The first feed back about the national PV-program that began in 2002 and combines a support at investment and feed in tariffs is eagerly expected. A general remark about the French PV funding is the difficulty to obtain a subvention and to be grid-connected with a feed-in tariff. The administrative burden that is associated with the demand of funding is a factor that slows down the deployment of renewable energies.

4.2.5 Description of the Italian situation

General context

Just like in France, the predominant application of PV in Italy up to now has been rural electrification (see Figure 4.15). Grid-connected PV has developed from the early nineties on but in first line for centralised applications for utilities use. Decentralised grid-connected PV underwent a huge increase in 2002 and represented over 50% of the PV installations in 2001 and over 90% of the installations in 2002.

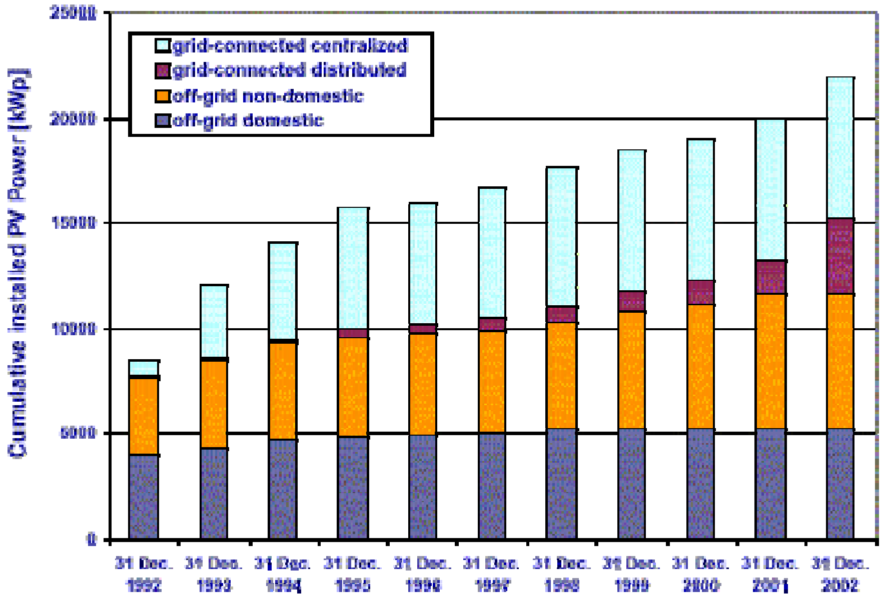


Figure 4.15*Cumulated installed PV power in Italy by submarket*

Table 4.7 *Budgets for R&D, demonstration programmes and market incentives in Italy*

	31/12/94 [kEuro]	31/12/95 [kEuro]	31/12/96 [kEuro]	31/12/97 [kEuro]	31/12/98 [kEuro]	31/12/99 [kEuro]	31/12/00 [kEuro]	31/12/01 [kEuro]	31/12/02k[kEuro]
National/ federal	17'000	17'000	5'000	5'000	5'500	5'500	5'800	30000	9000
State/ regional								10000	9000
TOTAL	17'000	17'000	5'000	5'000	5'500	5'500	5'800	40000	18000

The amount of funding for Italy before 2001 seems to be underestimated due to the difficulty to monitor regional activities in the field of renewables.

Analysis

The same remark as for France applies for Italy: for a private applicant to obtain funding, it takes a long time and lots of paper. This factor impacts a lot the decision of investors and shows the need to improve the efficacy of public support.

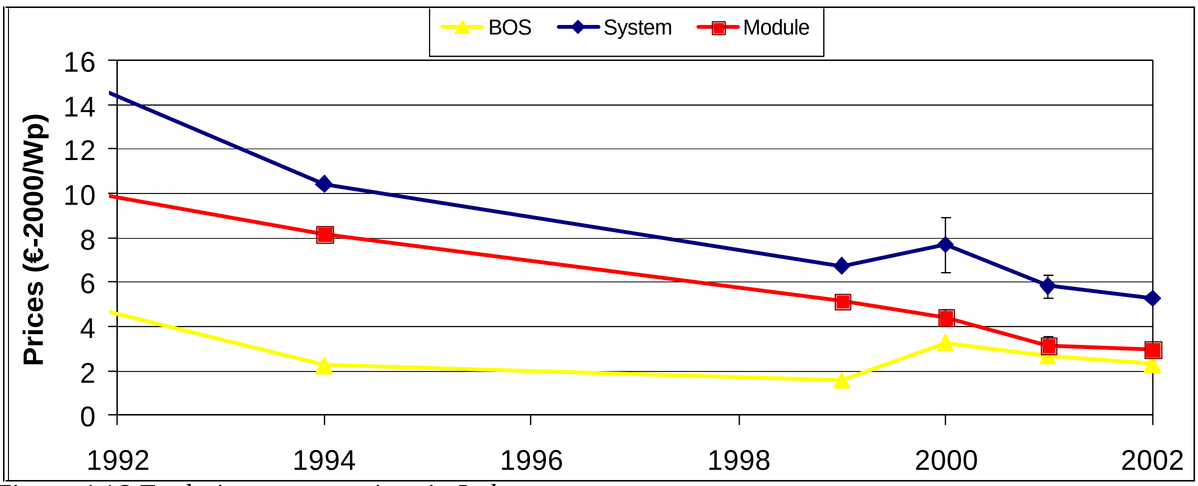


Figure 4.16 *Evolution system prices in Italy*

The price increase in BOS in Italy for 2000 and the high value of BOS price since then is related to the fact that smaller systems are now built where the BOS prices have a larger share.

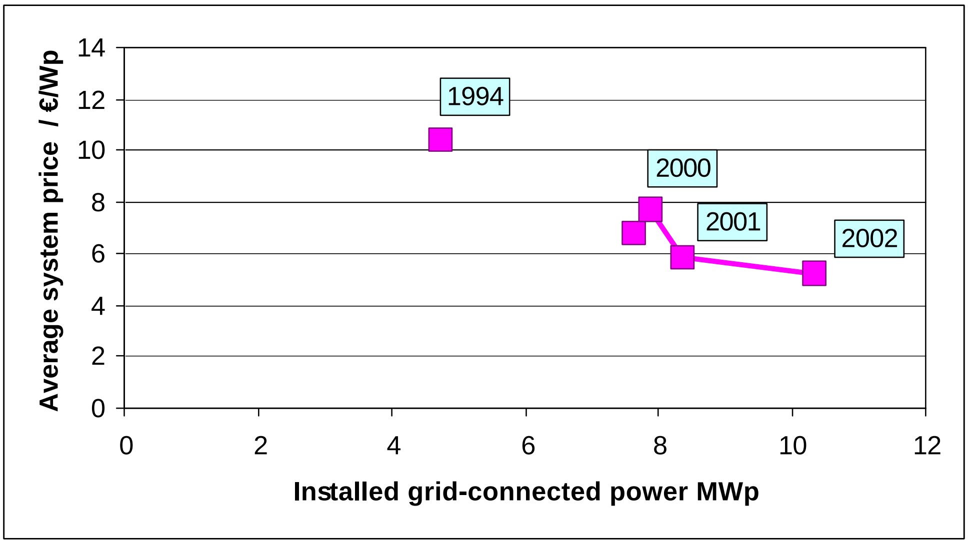


Figure 4.17 *Experience curve for grid-connected PV in Italy*

National programs data collection

Programme	Operating principle	Year of implementation	Budget (M€)	MWp installed
IT - Laws 308, 9, 10	Fiscal measure for self-production from RE, investment support for wide range of RE initiatives, new mechanism for supporting RE & updating of the related tariffs	1982 - 1999	1000 Meuro	No share available
IT - Isole minori	Investment support for projects in the field of RE and sustainable mobility on the small island of the Italian territory with funds coming from the Environmental Minister	2000 – on going	1.7 Meuro (energy) 1.25 Meuro (mobility)	280 kW
IT - Park	Investment support for projects in the field of RE and sustainable mobility on the parks of the Italian territory with funds coming from the Environmental Minister.	2002 – on going	2.5 Meuro (energy+mobility)	
IT - Tetti fotovoltaici	Investment support: - Public Administration, Private, small Municipalities and companies: tender open to the main municipalities of the Italian territory, capital support up to of 75% of the eligible costs with a maximum of 7.5 €/Wp installed (max 20 kW); - BIPV: open to private and P.A., maximum contribution of 85% (min 30kW) without eligible cost quota.	2001 – on going	Subprog. P.A.: 10 Meuro Subprog. Private: 20 Meuro Subprog. BIPV: 3 Meuro	2 MW (unofficial)

The lack of data for Italy concerning grid-connected decentralised systems makes the task of assessing any impact of the policies on system prices difficult.

4.3 Main conclusions historical analyses policy programs

4.3.1 Many different national strategies

One of the findings of this study is that the policies and programs are highly contextual and not easy to copy in one country for pasting in the other.

For example, in France, a large program for off-grid PV electrification took place with a strong impact on the price of secured PV systems. Similar conditions can be observed in Italy. But these kind of programmes cannot be pasted in the other EC member country since their geographical backgrounds are different.

For what concerns the incentives for grid-connected PV, the geographical differences do not apply much except for the fact that the solar energy resource repartition is inhomogeneous. The contrasts must be looked at on the level of the social acceptance for PV and of the degree of market liberalisation of the concerned country.

- The example of Germany clearly shows that a large program with attractive feed-in tariffs and soft loans is extremely effective in expanding the market.
- The number and variety of measures differs widely between the different countries. In France one single organisation centralises the whole actions for PV incentives with one only national programme combining subventions at installation and low feed-in tariffs. In the Netherlands, the number of different policies and programmes in favour of RE sources and particularly PV is huge.

4.3.2 Support and incentive programs cover system costs for PV in each country

A partial comparison of the measures efficiency in the different countries can be performed by comparing the evolution of the total funding for each new installed MWp in the different countries and the price evolution in relation to the national expenditure for the years 1999 to 2001.

Table 4.8 *Recapitulation of installed power, funding and prices*

Year		Share Grid Connected	Total installed power (MWp)	GC decentralised (MWp)	System price (€2000)	Module price (€2000)	BOS Price (€2000)	Total funding (M€)	Funding per MW (M€)	Funding per MW including commitment (3% inflation)
	DE	0,79	14	8,78	8,66	4,63	4,03	48	3,4	
1997	NL	0,42	0,78	0,33	10,21	6,16	4,05	13	16,7	
	DE	0,79	12,01	8,62	8,23	4,48	3,75	52	4,4	
1998	NL	0,81	2,44	1,99	11,06	6,55	4,51	22	9,0	
	FR	0,10	1,49	0,15	7,05	3,55	3,5	15	10,3	
1999	DE	0,85	15,6	11,8	7,32	4,25	3,07	50	3,2	
	NL	0,83	2,72	2,26	8,32	4,76	3,56	18	6,7	
	IT	0,31	0,8	0,13	6,73	5,15	1,58	5	6,5	
	FR	0,12	2,21	0,26	5,84	3,00	2,84	17	7,9	
2000	DE	0,95	44,3	40,8	7,42	4,45	2,97	77	1,7	7,9
	NL	0,95	3,56	3,19	8,47	6,00	2,47	21	5,8	
	IT	0,48	0,52	0,25	7,69	4,41	3,28	6	10,8	
	FR	0,14	2,53	0,36	5,54	2,9	2,64	17	6,8	
2001	DE	0,96	80,9	72,1	8,35	5,26	3,09	85	1,1	7,2
	NL	0,97	7,75	5,2	4,83	2,97	1,86	37	4,8	
	IT	0,48	1	0,48	5,81	3,18	2,63			
	FR	0,29	3,39	0,97	5,28	2,86	2,42	18	5,3	
2002	DE		83	83	6,42	4,57	1,85	105	1,3	7,1
	NL				4,83	3,17	1,66	16		
	IT				5,25	2,95	2,3	58		

For the exploitation of this Figure, we divided the total money spent in PV (funding and feed in tariffs) by the total installed power in the year, not taking into account the market segment. The ratio of the installed grid-connected systems on the total amount of installed PV differs widely from one country to the other. Since the average price for an off-grid system is over 20€/Wp, the funding for each new MWp is much higher in countries that made the political choice to support stand-alone systems (e.g. France in first line and Italy for which the ration of installed grid-connected PV are in 2001 respectively 15% and 52%).

Taking into account the commitment that is made of funding via the feed-in tariffs, the total funding for each new installed MWp in Germany is in the range of the other countries. Also the figure for the Netherlands in 2001 (4,8 €/Wp support) is a result of insufficient information due to the complexity of different support schemes. Many energy utilities were still giving subsidies out of that what remained from the MAP-funds after the year 2000. Furthermore, often municipalities also give an extra subsidy.

This results can lead to the conclusion that the amount of funding necessary to motivate the installation of PV must be in the range of 5-8 €/Wp (i.e. the price of the system) but that different policies provide this money via different mechanisms and have therefore different impacts on the number of yearly installed kWp.

4.3.3 Steady decrease of necessary market support per MWp

One result from Table 4.5 is also that in all countries, except Italy, the amount of funding for each new MWp installed is decreasing drastically. The case of Italy is related to the fact that there has been a strong emphasis in the past on large systems that had cost advantages on the volume purchase of modules and the BOS-prices in the mid 1990s. In later years the share of decentralised grid-connected systems was larger. Since 2000 also the system price is Italy is declining.

4.3.4 Shift from technology-push to market-pull policies

The measures are either becoming more and more efficient or moreover, the general trend of all countries tends to decrease the R&D funding for increasing market deployment incentives that are more effective in the short term. The next table for the case of Germany can illustrate this:

Table 4.9 *R&D versus market support in Germany*

Year	R&D vs. market volume M€/M€ in %
1991	514%
1992	207%
1993	200%
1994	119%
1995	74%
1996	48%
1997	37%
1998	53%
1999	39%
2000	21%
2001	12%

4.3.5 International spill-over in learning

On a European level, the inter-correlation of the different national policies was not put in light in the first part of the report. As a matter of fact, the experience curve of one country starts at a much lower price level than the one of another country if the market begins to develop later. It means that the experience curves of all European countries benefit from the big efforts in PV funding of one single of the member countries as is the case for Germany.

Table 4.10 *Year of achievement of the first MWp installed grid-connected PV and average price of the systems in this year*

Country	DE	NL	IT	FR
System price at 1MWp (€/Wp)	15 or more	10.3	7.6	5.6
Year of 1 MWp	Before 1992	1997	2000	2002

The table above illustrates well that countries that step in later at least partly profited from the experience gained in the frontrunner countries.

4.3.6 BOS-prices lowest in countries with largest markets

Some differences between the systems prices subsist between the four countries studied here (Table 4.1) and these differences can find their origin in the policies and strategies.

Table 4.11 *System, modules and BOS prices for the four countries of investigation*

	NL SYS	NL mod	NL BOS	DE sys	DE mod	DE BOS	FR sys	FR mod	FR BOS	IT sys	IT mod	IT BOS
1991				14,98								
1992				12,78	7,16	5,61						
1993	17,24	7,46	9,78	13,32	6,09	7,22						
1994	15,85			11,15	5,44	5,71						
1995	12,19			10,14	5,40	4,75						
1996	10,61			9,05	5,66	3,39						
1997	10,21	6,16	4,04	8,66	4,63	4,03						
1998	11,06	6,55	4,51	8,23	4,48	3,75						
1999	8,32	4,76	3,56	7,32	4,25	3,07	7,05	3,50	3,55	6,73	5,15	1,59
2000	8,47	6,00	2,48	7,42	4,45	2,97	5,84	2,84	3,00	7,69	4,41	3,28
2001	4,83	2,97	1,86	8,35	5,26	3,09	5,54	2,64	2,90	5,81	3,18	2,64
2002				6,42	4,57	1,85	5,28	2,86	2,41	5,25	2,95	2,30

From 2000 on for example, the BOS prices are much higher in Germany than in the Netherlands. The learning effect in the Netherlands for BOS is much quicker than in other countries, probably due to the implementation of the learning programme from 1996 on.

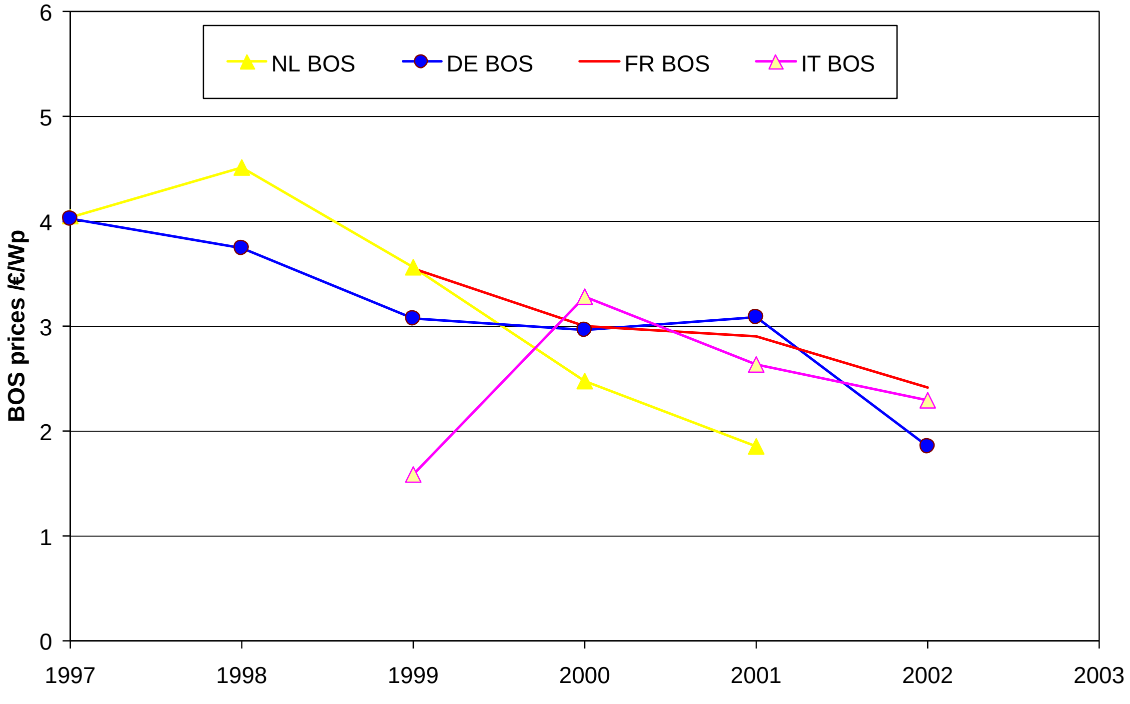


Figure 4.18 *BOS prices for the four European countries under investigation*[13] [14]

[13] The differences of BOS between the different countries can also be explained by the additional costs that are induced for the grid connection in the different countries. For example, costs for grid connection in Germany can amount from 50 to 500€ for one system in Germany while there is only a net-metering system in the Netherlands that leads to no additional costs. There is therefore a need in harmonisation of the grid connection procedures between the different countries.

[14] The low BOS-prices in Italy in 1999 are due to the fact that in that year mainly large systems are included, with some BOS-price advantages. The low French BOS-prices in 2000 and 2001 are related to an overrepresentation of systems in the database from the HIP-HIP program that only provided funding for very low-cost systems.

The price for BOS is higher in France and Italy than in Germany and the Netherlands in 2002. These high prices can be related to the fact that there is too little experience in installation and the part for handwork is therefore expensive. The discrepancies of BOS prices between the different countries could be smoothen by the creation of a kind of hand worker network for a better dissemination of the gained knowledge.

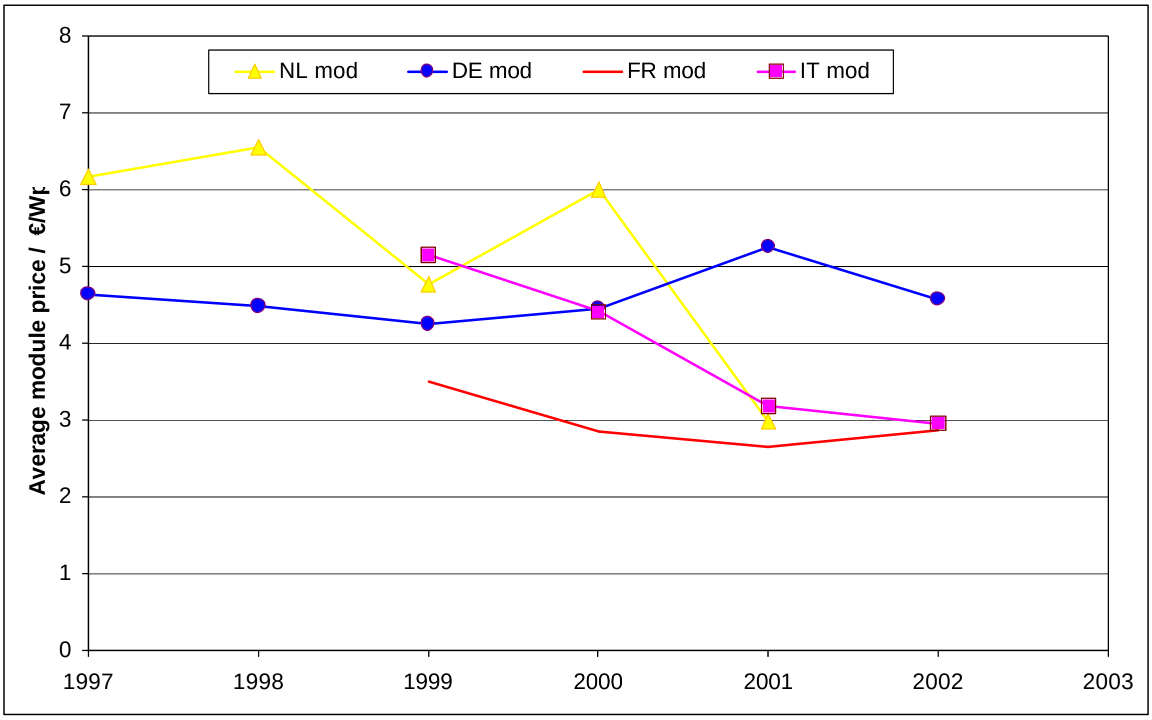


Figure 4.19 *Average module price in the countries of study*

4.3.7 Large increase in market support temporarily leads to higher module prices

For all countries addressed in this study, it could be observed that a high level short time funding is related to a punctual increase in demand that do not imply an increase in offer. Therefore, short-time local prices increase can be observed. This point speaks in favour of progressively increasing funding and long term policies that allow the building up of viable business plans. Concerning the module price, these short-lasting increases are observed in all countries. These increases are not occurring at the same time in the different countries and are therefore certainly related to the launching of new funding programmes.

5. EXPERIENCE-CURVE BASED PROJECTIONS FOR POLICY PURPOSES

5.1 Price projections

5.1.1 Comparison of bottom-up studies with simple experience curve price projections

One of the possible uses of experience curves is to project future prices of a technology in a certain future year by combining the progress ratio with an expected growth rate. Cost estimates for energy policy purposes normally are done by bottom-up engineering studies. Such studies have been done several times in the past for PV modules. In our study we started with a review of bottom-up price projection studies performed in the past, the oldest dating back to 1978. We have shown that such projections were generally too optimistic when compared with the actual developments. Figure 5.1 gives a comparison of the JPL cost studies from 1978-1985, with the actual status for the year 2000, based on a study by Arthur D. Little {Frantzis and Jones, 2000). A first conclusion that we can draw from this figure is that it seems to have taken until the year 2000 to achieve more or less the price projected for 1988-1992.

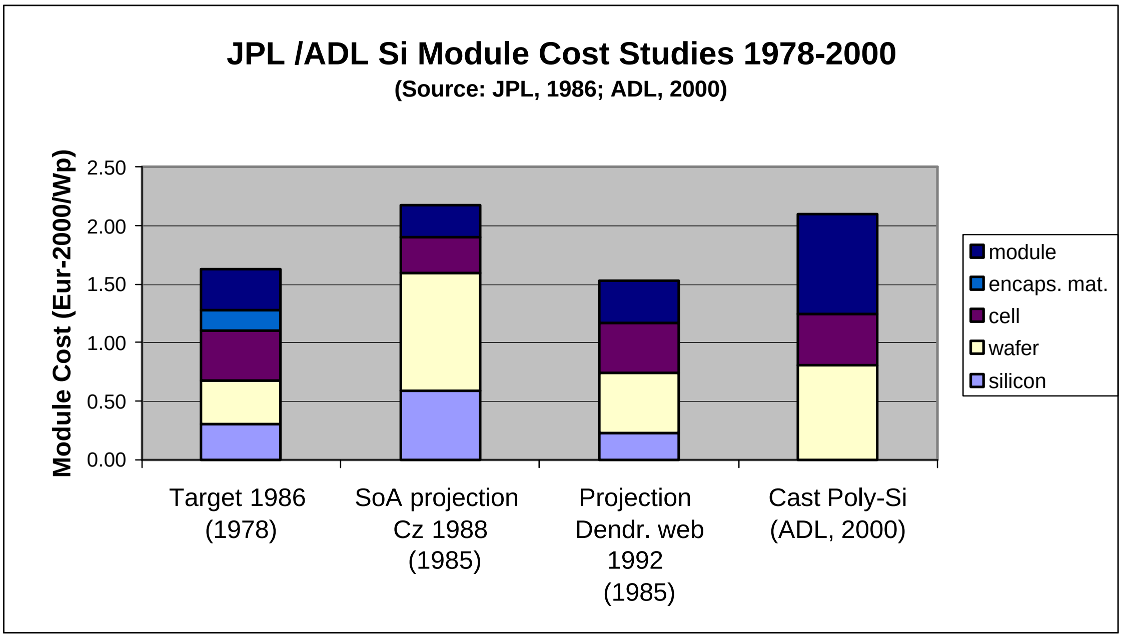


Figure 5.1 *Comparison of the JPL cost studies from 1978-1985 with the year 2000 state-of-the-art cost study by Arthur D. Little (Frantzis and Jones, 2000)*

The following table gives an overview of the cost projections of several of these bottom-up studies, the actual prices in the years projected and what would have been projected by an experience curve approach using the historic progress ratio and growth rate at the time of the projection[15].

[15] Note that prices are in general higher than manufacturing costs and furthermore, are subject to market forces. However, as manufacturing cost data are often confidential, average selling prices are a reasonable alternatives for comparison of costs projected and realised.

Table 5.1 *Comparison of bottom up and experience curve with the actual prices for PV modules*

Bottom-up Study	Year of study	Years statistics	Year of projection	Bottom-up cost projection ($/Wp)	Experience Curve cost projection ($/Wp)	Actual average selling price ($/Wp)
JBL86-31 target	1978	1976-1977	1986	1,63	0,86	11,94
JBL86-31 Cz	1985	1976-1984	1988	2,17	6,35	9.12
JBL86-31 Dendretic	1985	1976-1984	1992	1,02	2,80	7,70
EPRI 1986	1986	1976-1985	2000	1,50	0,79	5,05
MUSIC FM, 1996	1996	1976-1995	2000	1,00	4,07	4.05

What is clear from the table is that engineering studies have always been far too optimistic in assessing future costs. Progress in all parameters determining the costs (efficiency gains, production per m^2 costs, material and assembly costs) have been over-optimistic, if not in potential, then in timing. On the other hand, such price reduction paths were often more political statements than real scientifically based results. These studies, however, are valuable in determining where cost gains could be achieved, and as such helpful in policy making.

In certain cases business-as-usual learning curve extrapolation yielded results that were as bad. This was mainly due to the fact that in early stages of a technology over short periods very high growth rates (above 50%) occurred. Extrapolating these growth rates over time can lead to an excessive overestimation of technology progress over time. However, with a longer history of statistics, the match of experience curves-based projections with actual realisations can be pretty good when growth rates achieve more realistic and sustainable levels.

In conjunction with the prospective use of experience curves it is considered wise to perform bottom-up cost studies as well. The combination of bottom-up, technology-oriented cost reduction studies with the phenomenological and statistical approach of experience curves could provide extra credibility to the resulting projections.

5.1.2 Price scenarios for PV-systems

Since progress ratios nor growth rates can be assumed to be stable over time, the use of experience curves for projecting future price trends and assessing the cumulative learning investments needed, should include uncertainty analyses. One way to do this is by using scenarios. An example of different possible price developments of PV is illustrated in Figure 5.2: With a variation of PR and GR combinations, several price scenarios can be developed. A scenario developed by the European Photovoltaic Industry Association (EPIA/Greenpeace, 2002) scenario is also presented as a reference scenario.

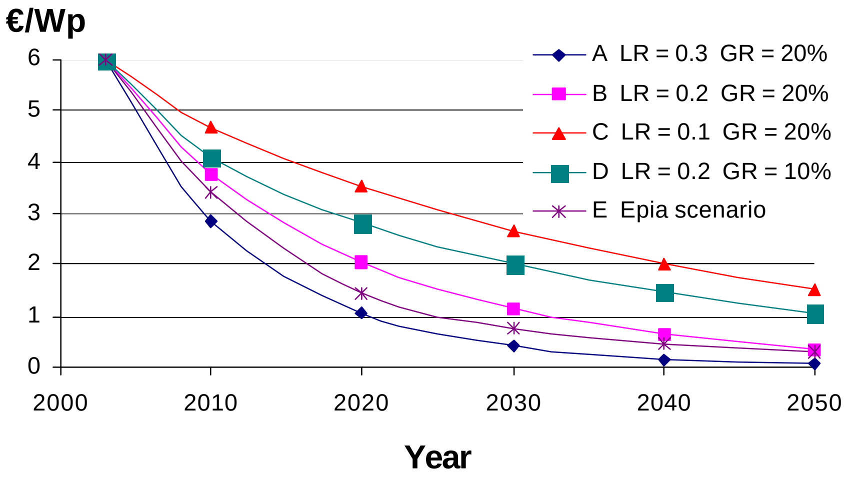


Figure 5.2 *Different price scenarios for PV-systems*

As can be seen in Figure 5.2, when an average growth rate of the annual shipments of 20% (common in the last decades) is used, a learning rate of 10% is too low to obtain low-cost PV in a reasonable time. Even with an LR of 20% the price decrease is slower than projected by EPIA/Greenpeace, unless a very ambitious implementation scheme is followed. Epia/Greenpeace extrapolated the more than 30% growht rates of the last five years until 2020 and concluded that even ambitious targets are within reach.

5.2 Sources of cost reduction and price forming up to 2010

To find out whether experience curve based price projections can be realised in the foreseeable future (up till 2010), bottom-up analyses can identify whether there are technical possibilities to do so. For this purpose a review has been made of more recent bottom-up cost studies for PV modules, inverters and other BOS components for residential systems and for large-scale systems.

5.2.1 Modules

General overview of manufacturing cost

Figure 5.3 gives an overview of the present-day (year 2000) cost structures for a number of PV module technologies. This overview is taken from the ADL study that includes:

- Direct manufacturing costs:
    - all materials and manufacturing labour, including first-level supervision
    - depreciation for manufacturing capital equipment and facilities.

Not included in the ADL cost values are:

- Other typical business costs (management staff and SG&A),

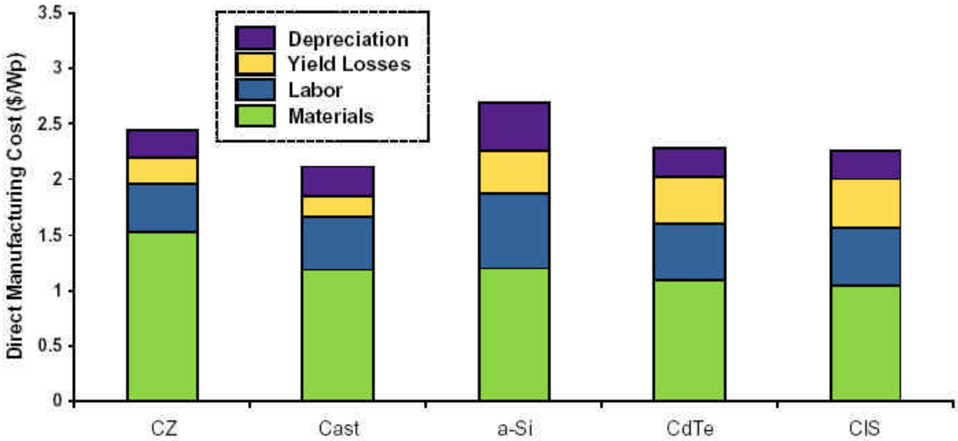
as these are a function of corporate strategy rather than technology.

We can see in Figure 5.3 is that about 50% of the cost is for materials and that also yield losses can be substantial, especially for thin film technology. Furthermore, it can be observed that an a-Si module has a low efficiency compared to a c-Si module. This is a major factor in the relatively high cost of a-Si modules.

Module Direct Manufacturing Cost Summary of Existing Cost Structures

Module Direct Manufacturing Costs for 10MW Plant in 2000

	CZ Silicon	Cast Silicon	a-Si	CdTe	CIS
Average Efficiency*	15%	14%	6%	8%	9%
Yield*	85%	85%	75%	65%	65%



*Stabilized cell efficiency for CZ and cast, and stabilized aperature area efficiency for thin films. Start-up yields for CdTe and CIS

Arthur D Little LFGlasgow 4/00 6

Figure 5.3 *Overview of the cost structures for present-day module technologies [Frantzis and Jones, 2000]*

Crystalline silicon technology

Figure 5.4 gives a more detailed breakdown of costs of multi-crystalline silicon (mc-Si) modules. Striking is the high material cost for the wafer production (70% of wafer cost), although module materials and labour costs are also substantial. If we analyse wafer cost in more detail we can establish that some 30% of the wafer cost are due to the high-purity silicon feedstock. The price of this feedstock, which is now in fact scrap material from the electronics industry, varies between 20 and 30 $/kg, depending on the market conditions within the integrated-circuit industry (Figure 5.4) If an independent supply of silicon feedstock for the PV industry could be realised at a price of 10-15 $/kg this would offer not only significant cost reductions and but also a more stable value for this important cost factor.

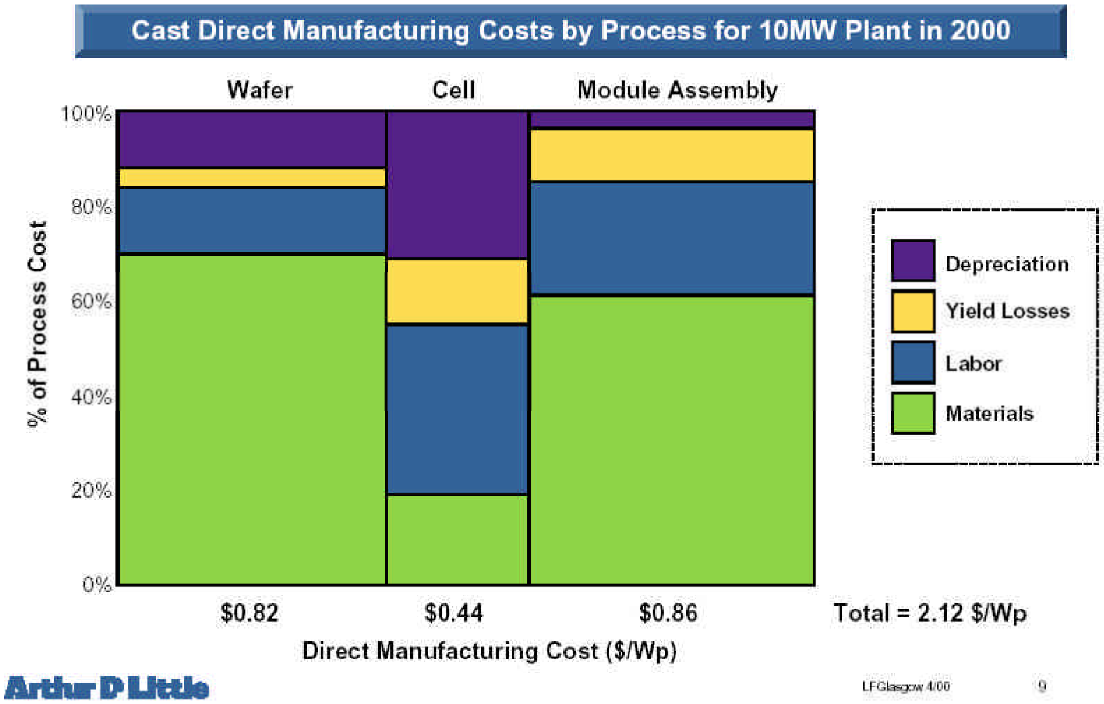


Figure 5.4 *Cost structure for multicrystalline silicon modules [Frantzis and Jones, 2000]*

A second way of reducing wafer cost would be by decreasing the amount of silicon required. It is expected that by reducing wafer thickness or by silicon "sheet" technology (RGS, EFG) Si requirements may be brought down from 17 g/Wp in 2000 to 10 g/Wp in 2010. Also improvements in crystallisation and wafering technology might help here.

Other sources of cost reduction are:

- Increased cell efficiency (from 12-14% -> 15-18%)
- Increased yield
- Lower labour cost by increased automation

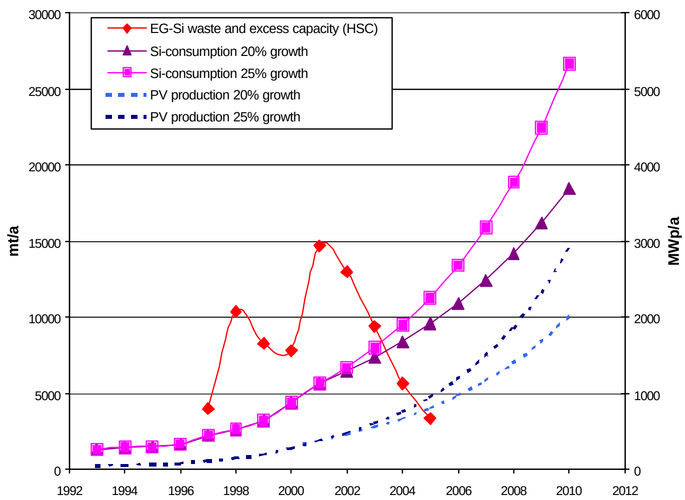


Figure 5.5 *Supply and consumption of high-purity silicon (EG-Si) for the PV industry*

A last option for cost reduction that we want to discuss is *plant up-scaling*. Figure 5.6 shows the expected effects of up-scaling based on the results of the MUSIC-FM study [Alonso, 1997]. We see that the primary benefits are expected in module manufacturing, probably due to the higher degree of automation in larger plants.

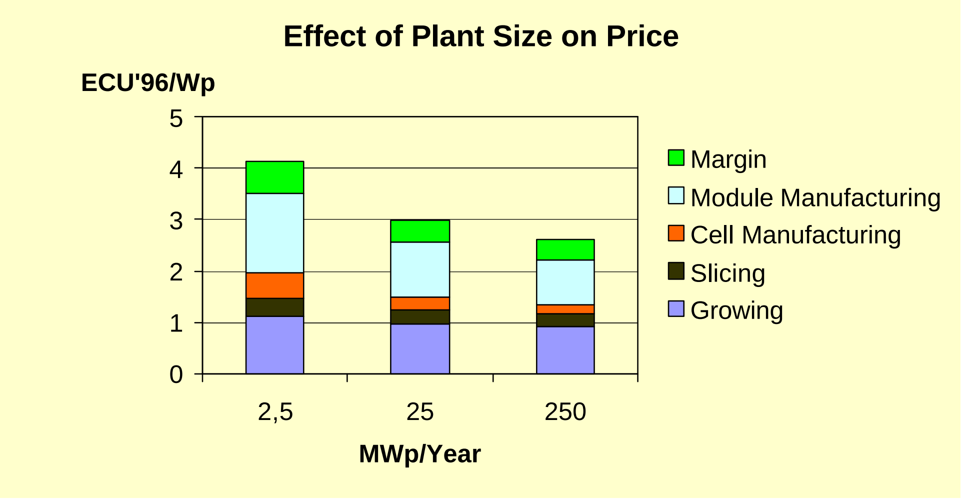


Figure 5.6 *Effects of plant up-scaling on module price (source: [Alonso et al., 1996], MUSIC-FM study)*

Figure 5.7 finally, gives an overview of cost reduction prospects for mc-Si modules until 2010. If we compare projections for *manufacturing cost* from ADL with the *price* projections by Maycock and EPIA (see same figure) we may note that a 40-100% needs to be applied for the overhead and the profit margin. Taking this price/cost difference into account the projections for 2010 seem fairly consistent.

In an update of the much-quoted MUSIC FM study Bruton projects module costs of 0.77 €/Wp for screen-printed multi-crystalline cells and 0.97 €/Wp for LBGB mono-crystalline cells, if manufactured at an annual throughput of 500 MWp/yr [Bruton, 2002]. Note that this is substantially lower than the 2010 projection by ADL, but this study assumed a less aggressive scaling-up (10->100 MWp/yr).
For the longer term, beyond 2010, we need additional research to establish which module prices may be ultimately feasible.

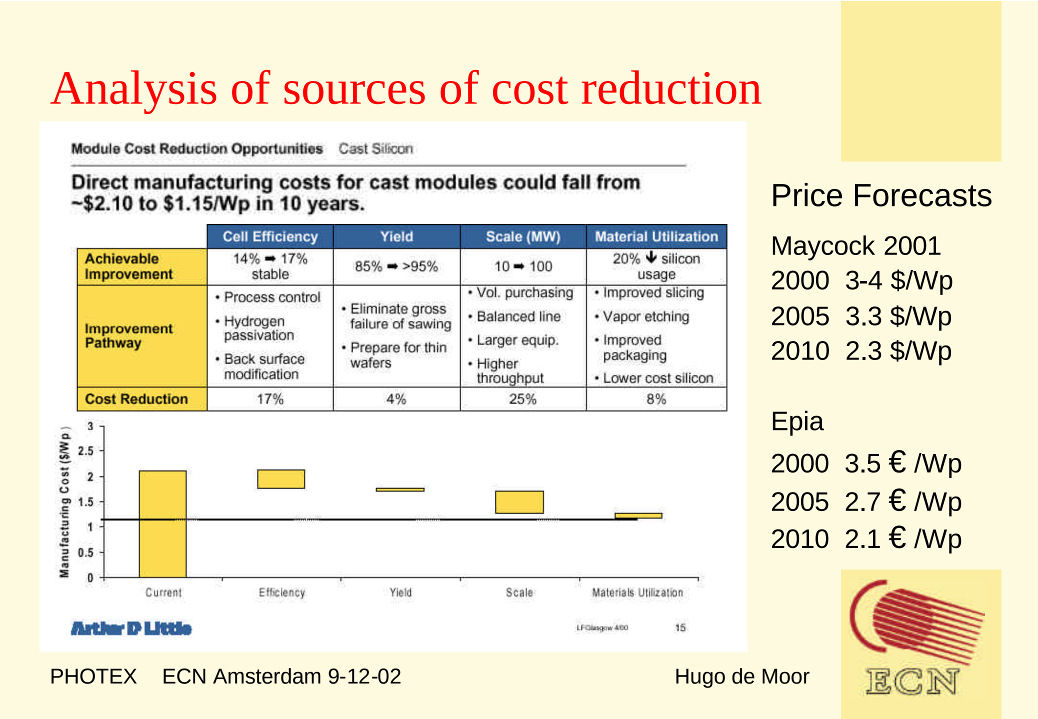


Figure 5.7 *Overview of cost reduction prospects for cast silicon modules. On the right are some price projections from Maycock and EPIA. Note that price includes overhead costs and profit and is therefore higher than direct manufacturing cost*

Based on these studies we conclude that direct manufacturing cost of modules which were around 2.1-2.7 €/Wp in 2002 may come down to 1.5-2.4 €/Wp in 2010. With respect to crystalline silicon technology improved silicon utilisation and low-cost silicon purification routes are considered essential, while for thin film technology improvement of stabilised module efficiency and process yields are of prime importance.

Total system prices for residential systems may come down from the current level of 4.5-4.8 €/Wp to 3 €/Wp in 2010, if the current level of progress in BOS learning can be maintained. For a large scale system like the Serre plant the system price would be around 4.1 €/Wp if it were newly constructed today.

5.2.2 Inverters

Introduction

The inverter of the PV system is – besides the modules – a major component of PV-systems. In fact in a breakdown of the BOS price it has a share of about 40% according to PHOTEX evaluation and other sources as well. The function of the inverter as part of the PV system is to adjust and convert the electrical features of the modules power output to the properties of the consumer system. In grid connected systems these properties are e.g. voltage, frequency, quality of current (noise) and safety regulations. These parameters and their tolerances and safety regulations can vary more or less strict even in grids by different utilities on a national level. Furthermore the PV inverter sets automatically the working to maximum production (MPP tracking). Sophisticated models include features to calculate production and failure statistics, and they are able for active and passive communicate with the operator or a centralised service station by using the telephone or even the power lines. This ability for remote maintenance, performance control, software updates etc. is also an important feature to minimize O&M price of the whole system. To conclude this brief introduction on PV inverters one can say that the system has changed from its original function of converting certain input voltages and frequencies to a given set of output voltage and frequency towards a multi purpose facility for power conversion, safety control, etc. Two generations of inverter technology is shown Figure 5.8: in the upper part a 1.1 kW_p inverter from the year 2000 is located on top of a 1.5 kW_p model from 1989.

Figure 5.8 *A 1,5 kW inverter from 1989 (bottom) and a modern 1.1 kW inverter (top) with far more functionalities*

Analysis of sources of cost reduction:

Looking for different options of cost reduction in the design and manufacturing process of PV inverters the classical examples of declining prices can be identified in the same way as in other technology sectors as well. This means savings due to learning, scaling and design effects:

- **learning effects:** increasing practice skill and experience of personnel in the chain from development to production. This results in a reduction of process time and improvement in the allocation of human and technological resources and material.
- **scaling effects:** The cost of series production increase less than proportional to the number of produced items for each charge. An improvement of set-up time for the production process which does not depend on the amount of items to be produced; reduction of waste material, idle times and commissioning times etc. Better logistics and an improved correlation between price and amount of purchased components by external suppliers.
- **design effects:** These apply to the organisation of the production process as well as to the product design itself. A standardised production process enables higher application of product specific tools. They streamline and clarify necessary process stages and enable a higher productivity. Modularity of the product family, accurate documentation and easy-to-install-features for service personnel and end users (plug&play) influence the commissioning and implementation procedure positively and reduce load on the support staff.

Small PV-inverters (smaller 5 kW)

This analysis reflects sources of cost reductions of PV inverters with a rated peak power up to 5 kW. This inverter size applies to small and medium sized systems in residential and commercial applications in the range of about 1 to 10 kW_p as well as to systems with rated peak power up to the Megawatt range. In the latter case a multitude of inverters with relatively low rated power are used. Example for this technical solutions are e.g. the 760 kW_p system of the Olympic stadium in Sydney using 900 PV inverters with 850 W_p or the 1-MW plant of the Academy Mont-Cenis in Herne, Germany where 569 inverters with 1500 W_p power feed the energy of about 3,200 PV modules into the grid.

Looking at the PV inverter as an artefact this can be split up into the following main components and subsystems:

- Box (metal or plastic)
- DC/DC-converter (boost converter or DC//DC with HF-transformer)
- Inverter-bridge (direct grid-connected like in Figure 5.9 or with NF-transformer grid connected)
- Output filter (consisting of capacitors and choke)
- Heat sink
- Digital controller (Micro-controller or DSP)

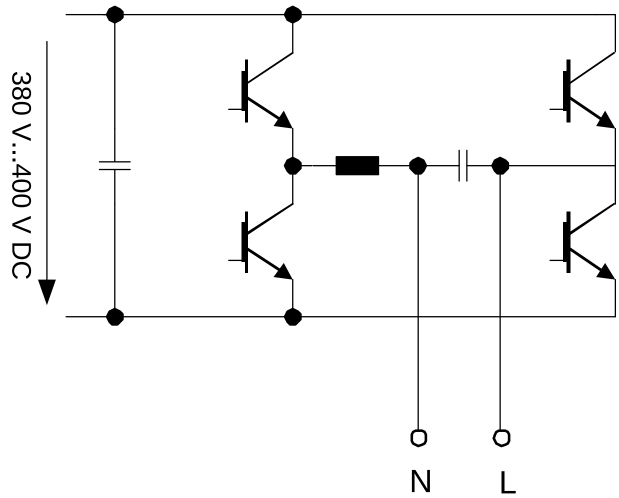


Figure 5.9 *An "H-Bridge" which is a typical part of an inverter without galvanic separation or with a high frequency (> 10 kHz) DC/DC-Transformer*

In the technical design of PV inverter following options are possibilities to reduce costs according to the categories mentioned above.

Optimisation of production technology of the inverter-box:
To reduce the material costs of the inverter housing material metal can be substituted with plastic. Because the cost for the form is very high this replacement is interesting only for high numbers of produced items. For the producing technologies roll-milling, punching and squirting plastics the initial cost and the cost reduction are different and depend on the produced amount of units. Roll-milling is favourable for small, punching for medium and plastic-squirting for a high number of units. Of course in every individual case it has to be proved if the used materials meet the requirements e.g. relating the claimed stability.

Many housings get their final shape by many work steps. The minimisation of these steps and the way to carry out an elementary housing design means a further potential to reduce costs. Furthermore work steps and thus working hours can be reduced by precise inspection of the sequences of operations at assembling of the individual groups.

Integration of the inverter in the PV-module
By abdication of the inverter housing costs for the housing drop out. In addition the installation work is reduced because the DC-cabling drop out too. The save potential per installed power is independent of the lot size because the economy of scale is negligible.

High Frequency DC/DC-Converters instead of Low Frequency Transformers
50 Hz-transformer (LF) for the galvanic separation and voltage adaptation is a well known and reliable technology for inverters. The electrical components and magnetic materials used for higher frequencies above 10 kHz are being improved continuously in recent years. These materials and components are used in high frequency (HF) – converters, which transform the energy by chopping the voltage. Therefore it is possible today to replace the LF transformer-technology by the HF-DC/DC-technology.

High voltage PV-modules
The present standard of PV-modules connection voltages is below 30 V. The modules can be switched in series connections. So the power of the single modules are added up. For grid connection with the simple, low cost and highly efficient bridge topology the inverter needs 380 Volt DC-voltage. This voltage level is for the installation of small power systems not practical because the power gets to high or the DC-voltage to low. Therefore the inverters contain two steps of energy transforming, e.g. a boost converter for the voltage adaptation up to 380 Volt and an additional full-bridge inverter. If the transmission can be done instead of two steps by just one step the device will have a higher efficiency, and, at the same time significant lower costs. For this application high voltage modules will have to be developed.

Abdication of galvanic separation with the grid
The realisation of the grid connection with a galvanic separating inverter can have different reasons.

- Safe separation between PV-module side and grid side is granted including higher contact safety.
- One point of the PV-modules can be grounded. The potential from the PV-modules to ground is fixed, no changes and no parasitic current is possible.
- Adaptation of voltage: the DC-voltage of the PV-panel is adapted to the grid voltage. This takes place either with a 50 Hz transformer at the output side (grid side) or by usage of a HF-transformer at the input side (PV-panel side).
- Prevention of feed-in of DC-current. The utility regulations for maximum permitted feed-in DC current vary in different countries.

The utilisation of electrical components of the last technology is leading to an increased switching frequency and this leads towards a constructional miniaturisation of the filter choke. If the size of the choke is below certain dimensions it can be fastened on the printed circuit board and the connection of cables to the according clamps can be omitted. This results in a shorter assembling process, furthermore material is saved. Additionally for an increased efficiency the dimensions of the heat sink can be reduced as well.

Other issues

- Use of optimised electrical components for the manufacturing process

  In industrial technology like e.g. drive technology in great quantities semiconductor modules are inserted. This enables a simplification of the board layout and a simplification of mounting and board assembling. The replacement of several semiconductor components by one semiconductor module will also lead to an accelerated production.

  For H-bridges which are used in most PV-inverters no optimal modules are being offered at present. With increasing demand of H-bridge modules they will be developed by semiconductor- and module manufacturers. Part of the semiconductor industry announced the availability of these kind of modules in the near future. These special modules will also help to reduce material cost.
- Three-phase inverters need clearly lower intermediate capacities

  Multilevel inverters show in general an intermediate direct currency link. The voltage oscillates periodical with the grid voltage. The oscillation depends on the capacity and may not exceed a certain limit of variation. If the current entry is carried out with three phases the intermediate direct currency link is burdened much more equally than with one phase. The capacity can be significantly reduced and the costs of material can be reduced too.

- General: with choice of topology cost minimisation possible

  Many different variations of circuits meet the standard function of PV-converter. Every version has its advantages and disadvantages especially concerning the material and production costs. Different requirements ask partially for contrary topologies.

Conclusion on inverter costs

For inverters the bottom-up cost analysis has identified a number of cost saving options among which the use of high-frequency dc/dc converters, high voltage PV modules, integration of semiconductor components and harmonisation of regulations. It is expected that inverter cost which are currently around 0.5 €/Wp for large systems to 0.8 €/Wp for smaller systems, can come down to 0.2 respectively 0.4 €/Wp. Given the modest progress ratios we have found, it is the question how fast these improvements will be realised. However, there are sufficient technical possibilities to get to these price levels.

5.2.3 Balance of System

As has been reported in Chapter 4, BOS-prices have been reduced dramatically in Germany and the Netherlands in recent years. It is the question how much room there is for further improvement.

Apart from the inverter, BOS-prices consist of:

- mounting and installation material
- mounting and installation labour
- planning and documentation

Mounting and installation material

Mounting structures have already realised a large part of their reduction potential. Most installers use standardised systems with little room for savings. Choosing galvanised steel instead of the use of aluminium profiles was the clue for the lower range systems. Examples of installation materials are plug connectors, string wires and module junction boxes. Further price reduction has to come from further integration of the components. If for instance the mounting structure is used as wire as well (as for instance in the concept of PV-Wirefree) some further price reductions can be made.

Mounting and installation labour

Labour during mounting can be slightly reduced. Modules could be clamped instead of bolted. Connection through pre-configured connectors speeds installation at higher material expenses. Most installers use already pre-mounting of module groups in the shop or large modules to reduce the mounting time on site. Cost for large modules is also little affected by additional cost for connectors. Some cost reduction for labour results from the availability of “ready to mount” modules. These are electrically safe for lay persons and can be mounted and connected by a roofer. A roofer generally is better skilled to work on a roof compared to an electrician. If the mounting is made very easy, one could even think of Do-It-Yourself kits, abolishing the labour costs. For flat roofs and AC Modules, this has already been shown possible in the Netherlands.

Planning and documentation

This issue is very dependent on the administrative culture of the specific country and the experience of the national and local bureaucracy with PV systems. In Germany this burden now has been reduced to below 0,1 €/Wp.

5.2.4 Large PV systems

MW-size PV systems have some fundamental pro’s and con’s with regard to costs. On the one hand additional costs with regard to Building Integrated PV systems are needed (e.g. land lease), on the other hand because of the larger volumes modules can be purchased for wholesale prices instead of retail prices. Currently large PV systems prices are in the same range of BIPV systems. There are several options for cost reduction.

Balance-of-system prices for large-scale grid connected systems
Most of the general comments on the technology reported in the section related to the BOS of residential systems can be adopted for LS system also; but there are differences. These differences have a strong impact on costs and economic evaluation. For instance, oversizing, bad project planning duplications of work, i.e. factors that are hidden in small-scale plants installation, become immediately clear in LS system project.

The construction of LS plants has the following important parts:

- the *design* of LS plant
    - criteria and sizing of the components are determined. The main design has often been maximisation of the plant efficiency. For LS plants "plug & play” components are not avalaible, except for the modules. This means that every other component has to be specifically designed. Furthermore, the difficulty to standardise technical solutions has important feedback on the general economy of the project. This means that in the field of the technical specification of the components’ and mounting possible costs reduction were achieved;
- the *Balance of System part*
    - power conditioners for LS PV systems are not standard available. Also, the electrical characteristics required (due the correct and efficient coupling with the PV generator) are studied time by time in the DC/AC architecture design. The supporting structures need to be designed as easy-to-mount and a simplification of the assembling procedures of modules is needed. Electrical boards (both DC and AC to connect the plant to the MV grid) need to be oriented to the simplicity and fast detection of the performance and failures that can occur during the plant operation. This is very important when the number of modules installed is high (by thousands) and from the same manufacturers (small difference in performance). Often, the plant monitoring system need to be adapted to the characteristics of the plant (i.e, tracking system as part of the arrays) which is not always obvious when standard commercial software is used.
- the *installation*
    - LS system *installation* is a highly critical phase of the project; it needs optimised procedures in the coordination of the construction site in order to reduce time and use of construction equipment.

Furthermore, for LS system, we can observe that the benefit in cost reduction due to scale economy is often negatively compensated by the lack of already available installation area's (as is the case for small scale systems): this means added costs due to ground preparation, foundation and civil works. From this point of view, an accurate site selection has sensible impact on the final costs.

Technical areas for possible costs reduction
Considering the architecture of grid-connected PV system, we investigate the technical areas in which costs reduction can be achieved.

Foundation and supporting structures:

- optimisation of the mechanical performance (weight, stress in the material, etc.) of the supporting structures & foundations during the design phase, searching the right balance between mechanical stress and steel/concrete sizing, adopting appropriate safety coefficients in order to reduce total amount of steel/bolts/concrete that impact both on purchasing and installation costs;

- since for LS plants it is useful to proceed to a pre-assembled phase for panels (steel + modules) before installation on the supporting structures, the mounting & transportation procedures need to be optimised. This item becomes important when the number of panels are very high in which case the pre-assembling location (site or factory) is not obvious.
- optimisation of the steel profiles mounting procedures on site in order to reduce the use of trucks and grains.

DC & AC electrical system:

- optimisation of the DC architecture in term of panels positioning, adequate strings wiring in order to reduce cables and the length of cable ducts;
- optimisation of the DC board architecture used for the parallel connection of the strings using appropriate electrical characteristics for the protections both on DC and AC. Most of the electrical designers are not completely familiar with high DC voltage & current: this means, in general, oversizing in boards components;
- use of standardised components for the more classical AC side, investigating the right balance between the real electrical performance required by the PV system and the range of products generally used in MV grid by the utilities.

Power conditioning:

- evaluation of the economic convenience in utilising the centralised power conditioning or the string conversion in term of reliability, global efficiency and maintenance during the plant operation;
- optimisation of the power rating of the inverter vs. PV power output in order to reduce size and cost of the inverter/s.

Testing & Commissioning

- appropriate design & technical specifications can reduce the costs of the necessary acceptance tests activities both on factories (modules, inverter, boards, steel, etc.) and on field (strings I-V curve, sub-array performance, etc.);
- optimisation of the test-run procedures during commissioning of the plant (remote control & acquisition vs. personnel on site, etc.)

Data Acquistion System

- Optimisation in the Data Acquisition System design using commercial equipment and architecture instead of dedicated Software & Hardware in order to reduce the cost of maintenance during the plant operation;
- extend as much as possible the use of the remote controls for the plant operation

5.3 Conclusions price projections up to 2010

5.3.1 Sufficient technical options for modules, inverters and BOS

The European Photovoltaic Industry Association EPIA has set cost targets for 2010. For modules they expect a cost of 2.1 Euro/Wp and for total systems they expect about 3.4 Euro/Wp.

With regard to modules, bottom-up studies have shown that in principle there are enough possibilities to reach a direct manufacturing cost level (i.e. costs without organisational overhead costs nor R&D-costs) of 1.15 –1.40 €/Wp for crystalline silicon and amorphous silicon technology. Critical technological factors for c-Si cost reduction are dedicated silicon feedstock processes and reduction of silicon requirements through thinner wafers and silicon sheet processes. The effect of up-scaling for c-Si technology has also been investigated, showing that the primary benefits are expected in module manufacturing, probably due to the higher degree of automation in larger plants.

In 2000 the selling price of inverters in the 1-2 kW range was about € 1200-1000 per kW_{AC} (Meinhardt et al., 2001). Larger inverters sell at lower prices, i.e. € 800 kW for a 16 kW inverter. SMA, the largest European inverter manufacturer has indicated that it wants to reduce inverter costs by 50% until 2006. This will be done mainly by advantages offered by mass production. They further state that cost reduction to less than € 250 per kW_{AC} does not seem possible with today's technologies. Possible breakthrough technologies leading to even lower cost inverters are complete integration of inverters with a module, high-frequency converters and high voltage converters (which need the development of high-voltage PV modules). These more radical solutions are expected to have impact after 2010.

With regard to BOS-prices a large part of the cost reduction potential seems to have been realised, at least in Germany and the Netherlands. Clue to further reduction will be further integration of components or reduction of the number of components by smarter designs. However, at least for the medium-term future, the largest part of the reduction for PV-systems has to come from reduction of the price of the modules.

Large PV systems have shown to be able to keep the pace of price developments of smaller PV systems.

5.3.2 Prices in coming decade will be influenced by many factors

The analysis above indicates that there is enough technical potential to bring costs down. However, prices will be influenced by factors not directly related to direct production costs. Three different factors that can be discussed are:

1. End of forward pricing might slow price trend down
Until now PV module producers have always indicated that instead of making profit on their module sales, they are still dealing with losses. If this is the case, this can be understood if considering that the large majority of the dominant PV-module manufacturers are relatively small departments of very large multi-national enterprises with their core businesses for instance in oil or electronic equipment. Until today these enterprises have seen their PV-businesses as a strategic investment in the future that can afford losses for some time ('forward pricing'). However, the market of PV is growing so rapidly, that the amounts of money involved start to become substantial, also for these large multinational enterprises. Remarks from industry participants during interactive sessions in the Photex-project indicate that the projected time-frame to get in black figures for the PV-departments is very close to today (2004-2005). This process can be visualised as follows:

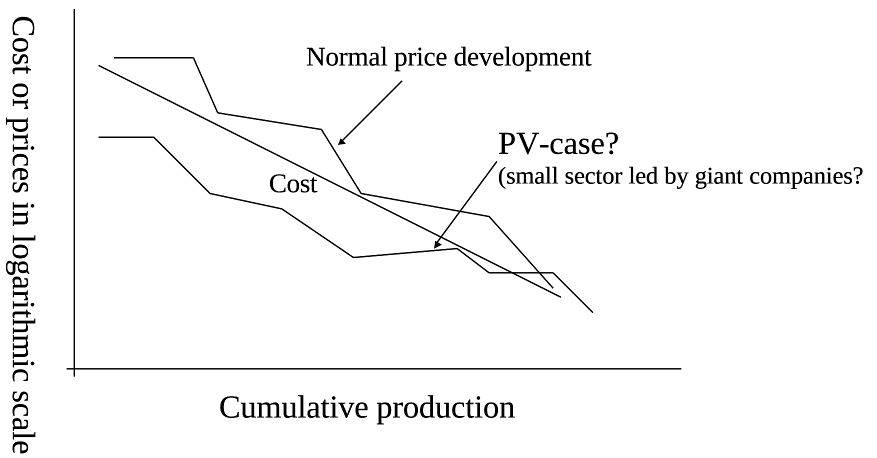


Figure 5.10 *The rather specific nature of the relationship between prices and cost in the PV-industry*

This means that, if in the coming decade prices have to cross the cost line, the trends in prices that will be observed in the near future could be less favourable than the underlying cost trend.

2. A shortage in silicon supply might drive up PV-module production costs.

Traditionally the demand for silicon from the PV-industry has been orders of magnitude lower than demand for silicon for the ICT market The PV industry used to use waste from silicon production processes for ICT purposes as a feedstock. However, if PV continues to grow with growth rates of 15% or higher, the demand for silicon from the PV-industry will be comparable to that of the ICT industry pretty soon. Therefore PV-dedicated production processes will have to come on-line in the next few years, otherwise a supply shortage of silicon might lead to higher PV-module prices. These new production facilities will have to produce PV-silicon wafers for costs that are substantially lower than can be expected from the ICT-industry. This might be possible, because impurity levels of silicon for the PV-application can be higher than for ICT applications.

3. Possible overcapacity in case of lower demand

Because of the soaring demand of the last few years, many PV module producers are expanding their production capacity rapidly (while sometimes closing down smaller and older production locations). In case the current growth rates of about 30% are not maintained, possibly a production overcapacity might develop. In that case prices in the market will come under pressure.

6. BALANCING MARKET SUPPORT AND RTD ACTIONS

One of the core questions in energy policy is how to strike a proper balance between RTD actions, directly aimed at technology development (a "technology push" effect) and stimulation of market penetration (a "demand pull" effect). As we will see in this chapter, this question is part of a wider question, i.e. how to design a well-balanced portfolio of measures to support the development of socially desirable technologies, i.c. PV. Without claiming to have any final answers to this question, this report will try to elaborate on some considerations policy makers might want to take into account when developing or analysing their portfolio of support measures.

6.1 Approach

The first step of the analysis is to make a theoretical qualitative model of learning in the PV-industry. This will be based on a combination of what is known in general on technology innovation dynamics and learning mechanisms on the one hand (see section 1.3) and the inside knowledge of the workings of the PV industry represented in the Photex-project team on the other hand.

The qualitative model in itself immediately leads to reflections on what a well-balanced portfolio of support measures could look like. To see what this means for the case of PV a more quantitative approach has been developed, using a spreadsheet model based on the experience curve approach. For the case of PV some quantitative explorations will be made. Starting from extrapolating the business-as-usual scenario into the future, several alternative scenarios are explored and potential benefits for technology development, market acceleration and public/societal expenditures will be analysed.

6.2 A dynamic learning diagram for the PV-industry

Figure 6.1 shows a diagram, developed within the Photex project, depicting the learning processes in the PV-industry. In fact it is a version of the diagram shown in Chapter 1 (Figure 1.2) with the two other learning-mechanisms (learning-by-interacting and learning-by-using) and including the PV production column.

Public and private expenditures into R&D enhance the learning-by-searching processes that add, together with the results of learning-by-doing in the production processes to the stock of technological knowledge by which producers of PV-modules can reduce their costs. Cost can be reduced by reducing capital costs (new, larger and improved production plants), reducing labour costs (more automated processes, more efficient work processes) and by reducing on material costs (improved designs and production processes, improved recovery of materials).

Public and private expenditures on the demand side lead to more installations of PV-systems. As users gain more experience and share their knowledge of installation and operation, operation procedures can be improved. Learning-by-interacting currently mainly happens at conferences and renewable energy technology fairs. These places tend to be visited primarily by people from the PV-producers, the research community and some large consultants.

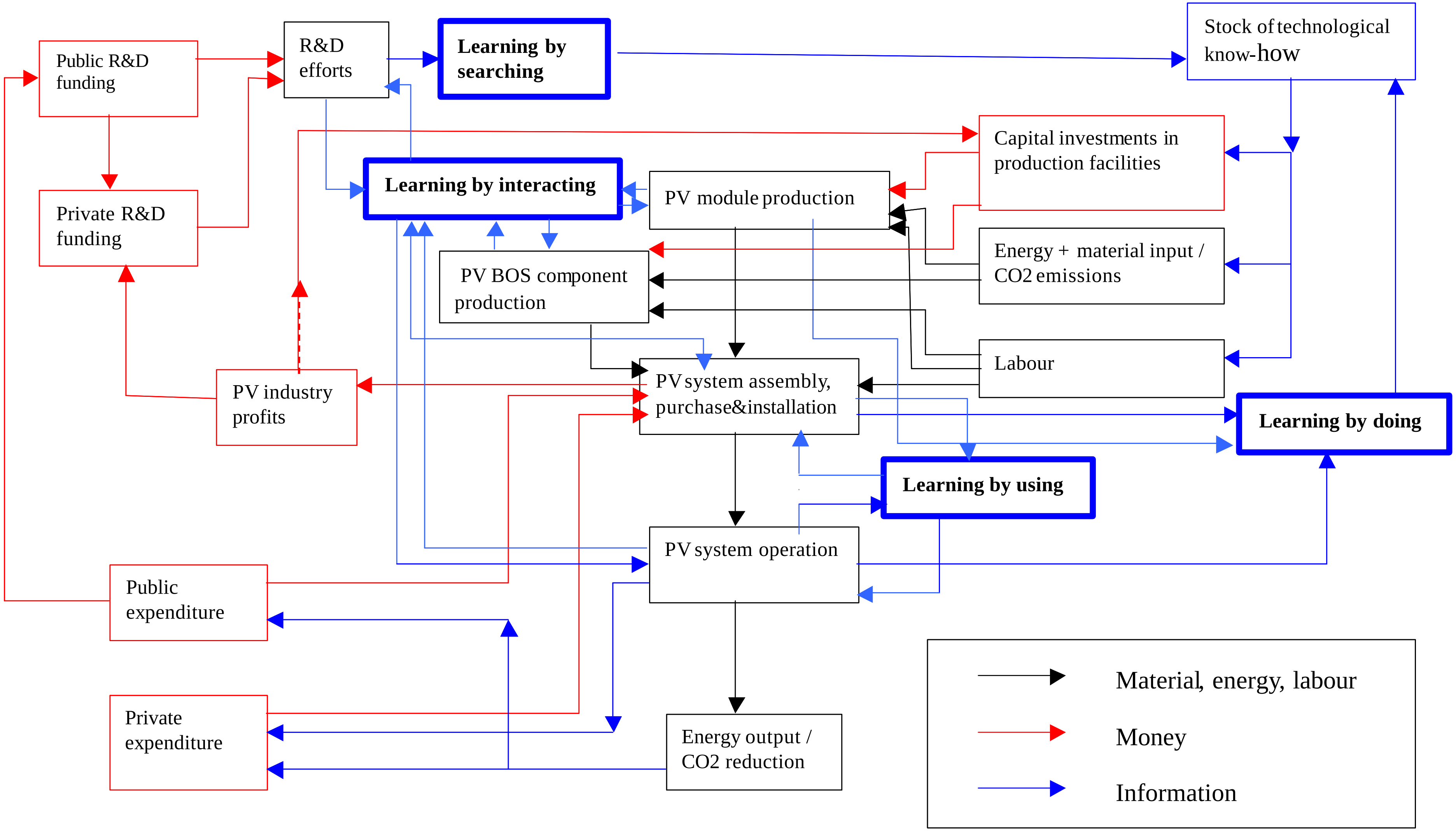


Figure 6.1 *Dynamic model of learning in PV industry*

6.2.1 Direct policy support primarily to two classical learning mechanisms

As can be seen from Figure 6.1 the main learning mechanisms supported by public expenditure are learning-by-searching and learning-by-doing, the former by supporting PV R&D and the latter by supporting the development of the market. As we have seen in WP4 there are different levels and ways of market or R&D-support, all with their own characteristics.

6.2.2 Shift from supporting learning-by-searching to learning-by-doing

A general trend of the last decade is that public expenditure, especially in countries as Germany and the Netherlands has shifted in a relative sense from supporting R&D to supporting market development. Currently the ratio in a country as Germany is about 10 Euro spent on market support versus 1 Euro on R&D. This shift has been successful in enhancing the progress ratio of BOS in these countries. Now the main part of the PV-system cost lies in the science-based production of modules. Balancing R&D-support again with market support might improve the progress ratio further.

6.2.3 Learning can be improved by supporting learning-by-using and learning-by-interacting

What can also be seen from Figure 6.1 is that there is far less direct support for the other two learning mechanisms: learning-by-using and learning-by-interacting. Sharing of user knowledge however is barely organised yet and happens maybe only through informal networks[16]. This means that learning-by-using could be supported more. In Chapter 4 it has been analysed that the feed-back from users to industry and the research community has been explicitly organised during a certain period within subsidised projects in the Netherlands and has been left to market forces in Germany. Because of the large market size in Germany this spillover of knowledge in informal networks has compensated for the lack of supported organised feedback structures. In the Netherlands the smaller size of the market (compared to Germany) has been compensated by additional investments in learning programs. A combination of the two can expected to be even more effective in enhancing the learning process.

Possible measures that could enhance the learning process by directly supporting learning-by-using and learning-by-interacting are:

- stimulate and support the foundation and workings of PV user groups
- stimulate and support networks between PV-producers and the users of their products
- organise workshops, support user journals etc.
- support education and training programs for technicians, engineers, consumers, business decision-makers and scientists
- support the development of technical standard committees representing all the relevant groups (i.e. users, producers, researchers, installers etc.)

In European programs the Concerto and Intelligent Energy for Europe initiatives certainly have elements that cover learning-by-interacting and learning-by-using. It will be a challenge to include in these programs actors that until now have not been included in the EU programs, but are certainly relevant for technology learning processes (consumers, SME's etc.).

6.2.4 Stimulation of international learning on the Balance of System (BOS) part

Another important support option from a European point of view is to support international learning on the BOS-side. As we have seen BOS-learning is mainly national, but international spillovers do occur. Projects that support the dissemination of knowledge (e.g. by the creation of international knowledge networks on BOS-issues) over country borders can help countries that are about to start to develop their market enormously in reducing the costs of their programs.

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[16] The phrase 'PV user club' or 'PV user forum' does not give any hit in Google for instance.

6.3 Quantitative explorations into the future

For the purpose of quantitative explorations a spreadsheet model has been developed. It can make price projections for PV-technology, using different scenarios. Also an estimate can be made, what an improved progress ratio means in terms of the reduction of the total learning investment needed. It should be noted that the tool has been inspired by the work reported in van der Zwaan and Rabl (2003).

In this section, first the spreadsheet model will be described and then some major results will be presented and analysed. The spreadsheet is freely available from the internet and is free for use, under the condition that reference is made to it anytime results derived from this spreadsheet are presented publicly. (www.energytransition.info/photex)

6.3.1 Description of the spreadsheet model

Purpose of the spreadsheet

The purpose of the spreadsheet is to serve as a calculation tool for PV-price projections using the experience curve approach. By changing the input characteristics, it can be used for any other renewable energy technology without fuel costs.

Basic assumptions

1. Progress ratio is fixed throughout the entire time horizon.
2. Annual growth rate is fixed throughout the entire time horizon.
3. Aggregation to PV *systems as a whole* on a global level rather than differentiating between PV modules, BOS-components, and installation. In principle this is not in line with our earlier suggestion made in section 2.3. However, in order to estimate break-even outputs, the whole system has to be taken into account. Also, progress ratios for modules at a global level and BOS at the different country levels has shown similar progress ratios of around 80%.
4. No distinction for the size or location (climate) of a PV system.
5. Cost for storage, back-up power or ICT-based demand response technology, needed in case of high penetration levels of intermittent PV in the electricity grids have not been taken into account
6. External cost of the competing energy technologies is not included or addressed (as part of the break-even level).
7. In the base case, the costs are not discounted over time. The possibility of introducing a discount rate however is included.

Inputs

There are four input categories in this spreadsheet. (Input fields are coloured in green).

1. input characterising economic scenario
    - discount rate (put at zero in the base case)
2. input characterising the technology
    - global cumulative capacity in start year 2002
    - system price at the end of start year 2002
3. input characterising the market to be investigated
    - financial characteristics of this market
        a. depreciation period
        b. interest rate
        c. O&M-costs (in Eurocent/kWh)
        d. Price of competition (in Eurocent/kWh)
    - geographical characteristics
        a. Capacity factor
4. input characterising the scenario. There is room in this spreadsheet to compare three scenarios with each other. Each scenario is characterised by a combination of:

- progress ratio
- growth rate

Outputs

There are three output categories in this spreadsheet. (Output fields are coloured in blue)

1. outputs characterising the break-even situation for the described market
   - the break-even specific system costs (result of the market characteristics)[17]
   - the break-even year
   - characteristics of the cumulative learning capacity
     a. the break-even cumulative capacity
     b. comparison of break-even capacity with global power capacity in 2002
     c. electricity annually produced from this cumulatively installed capacity
     d. comparison of c. with annual electricity production in 2002
   - total learning investment (calculated by summing the products of the average price in a year (minus the break-even specific system prices) and the installed capacity in a year of all the years in which break-even is not yet reached).
2. outputs reflecting the value of investing in improving the learning rate/progress ratio (i.e. the value in investing in R&D, dissemination of knowledge, creation of knowledge networks etc.)
   - gain on learning investment needed compared to BAU scenario
   - annual gain on learning investment needed compared to BAU scenario
3. outputs giving market projections from 2010 to 2050
   - price projections
   - cumulative installed capacity in GW
   - annual market size in GW

[17] The break-even specific system costs is calculated according to the levelised cost approach: SSC = AT/CRF, with SSC is specific system costs, AT = Annual Turnover and CRF is the Capital Recovery Factor. AT = (8.760*Capacity Factor)*(Price per kWh produced - O&M costs per kWh) and CRF = $I + I/(1+I)^{DP-1}$, with I = interest rate and DP = Depreciation Period of the investement.

Inputs				
Technology characteristics (e.g. PV)				
Cumulative capacity 2002 (GW)			2,35	
Specific system cost 2002 (Euro2002/Wp)			6	
Market characteristics (e.g. bulk electricity market in Southern Europe)				
Depreciation period			15	
Interest rate			8%	
O&M-costs (Euro2002/kWh)			0,002	
Competitive price (Euro2002/kWh)			0,05	
Capacity Factor			0,19	
Scenarios		BAU	Alternative 1	Alternative 2
Progress ratio		0,8	0,75	0,7
Growth rate		0,2	0,2	0,2
Results				
Break-even outputs				
Break-even specific system costs (Euro/Wp)	0,7			
break-even year		2039	2031	2025
total learning capacity (GW)		1999	465	156
total learning capacity as % of current global production capacity (3300 GW)		60,6%	14,1%	4,7%
Total annual learning production of electricity (TWh/yr)		3327	774	259
Total annual learning production as % of current global production (15000 TWh)		22,2%	5,2%	1,7%
Total learning investment (billions Euro2002)		632	192	89
The value of investing in learning processes that improve progress ratio				
Gain on learning investment with regard to BAU case (billions Euro2002)		0	441	543
Annual gain on learning investment with regard to BAU case (billions Euro2002)		0	15,2	23,6
Projections				
Projected specific system costs				
	2010	3,75	3,28	2,83
	2020	2,09	1,54	1,11
	2030	1,16	0,72	0,43
	2040	0,64	0,34	0,17
	2050	0,36	0,16	0,07
Cumulative installed capacity (GW)				
	2010	10	10	10
	2020	63	63	63
	2030	387	387	387
	2040	2399	2399	2399
	2050	14851	14851	14851
Size of the market (GW)				
	2010	1,7	1,7	1,7
	2020	10,4	10,4	10,4
	2030	65	65	64,6
	2040	400	400	399,8
	2050	2475	2475	2475

Figure 6.2 *Photex spreadsheet model: example of inputs and results of one case*

6.3.2 Main results of quantitative analysis

The case of the bulk electricity market

A first case to study is to see when and under what scenarios PV will become cost-competitive for the bulk electricity market in countries with a high solar irradiation. The market conditions are then shown in Table 6.1[18].

Table 6.1 *Market characteristics for bulk electricity market in solar-rich regions*

Depreciation period	15
Interest rate	8%
O&M-costs (Euro2002/kWh)	0,002
Competitive price (Euro2002/kWh)	0,05
Capacity Factor	0,19

A depreciation period of 15 years and a required interest rate of 8% corresponds to investment requirements for stable secure investments (corresponding for instance to the current investment requirements in the German wind energy sector). This means that it is assumed that by the time of market break-even the technology can be completely trusted, and firm long-term contracts of 5 cents/kWh can be negotiated. The price assumed is 2 cents/kWh above the current power exchange prices, reflecting the expectation that in the mid-term to long-term electricity prices will increase somewhat, due to the reduction of the current over-capacity in the European electricity market resulting in current prices that only reflect short-term marginal costs.

[18] This is the case of Figure 6.2.

These market characteristics lead to a break-even capital cost price of about 0,7 Euro/Wp. Table 6.1 summarises the results.

Table 6.2 *Break-even years, learning investments and PV market share at break-even for the case of the bulk electricity market in Southern Europe*

	GR=0,1	GR=0,15	GR=0,2	GR=0,25	GR=0,3	Global cumulative learning investment (10^9 Euro)	Break-even annual PV electricity production (% of 15000 TWh)
PR=0,9	2152	2104	2080	2066	2056	$3,3 * 10^6$	40000
PR=0,85	2099	2068	2053	2044	2037	5193	275
PR=0,8	2073	2050	2039	2032	2028	634	22
PR=0,75	2057	2039	2031	2025	2022	193	5
PR=0,7	2046	2032	2025	2021	2018	89	2

The shaded cells represent the calculation for the business-as-usual case (extrapolation of the past 25 years). There are several conclusions to be drawn from this table:

1. Simple extrapolation of the trend of the past 25 years indicates that PV will become economically available for the bulk electricity market around 2040. Global learning investments to reach this will be in the order of 600 billion Euros/dollars. To reach this target about 22% of the global electricity production will have to come from solar PV electricity (if electricity consumption stays at the level of today).
2. If the progress ratio deteriorates to a level worse than 80%, it is not realistic to expect that PV will ever reach the point of break-even.
3. Market growth rates should be 15% or higher to make sure that a break-even situation will be reached before the second half of the 21st century.
4. With an improvement of the progress ratio to about 75% (which is close to the average of the last decade) PV will become economically available for the bulk electricity market around 2030. What is more, learning investments needed will be about 400 billion Euros/dollars less than in the business-as-usual case. Every dollar/Euro spent on improving the progress ratio (by supporting R&D, learning-by-using and learning-by-interacting) less than 400 billion Euro over the coming 25 years (which is 15 billion annually) will be a saving for society. For comparison, the cumulative global R&D-expenditures on PV between 1975 and 1999 has been in the order of 5 billion USD (Teem-database, 1999). Also, with a progress ratio of 75%, the annual electricity production needed to come from PV in the break-even situation is reduced from 22% to a more realistic 5% of the current global electricity production.
5. If the high growth rate of the recent years of about 30% can be combined with a progress ratio of 75% or better (made possible by enhancing the support of R&D, learning-by-using and learning-by-interacting) PV can become cost-competitive within 15 to 25 years.

In the case of PV, enhancing investing in learning processes by supporting R&D, learning-by-using and learning-by-interacting processes, seems to be a good choice from a public policy point of view. The savings in the market support needed will largely offset spending on these issues. Such an investment has to be combined with a market policy resulting in at least 15% growth rate, but preferably in a higher growth rate.

Reducing learning investment costs by aiming at high-value markets first
What Table 6.1 indicates as well is that the bulk electricity market is not the first market for PV to go for. The learning investment needed can be reduced as well by first aiming at competitive niche-markets, a point also made for instance by Poponi (2003) and van der Zwaan and Rabl (2004), and illustrated in the next Figure:

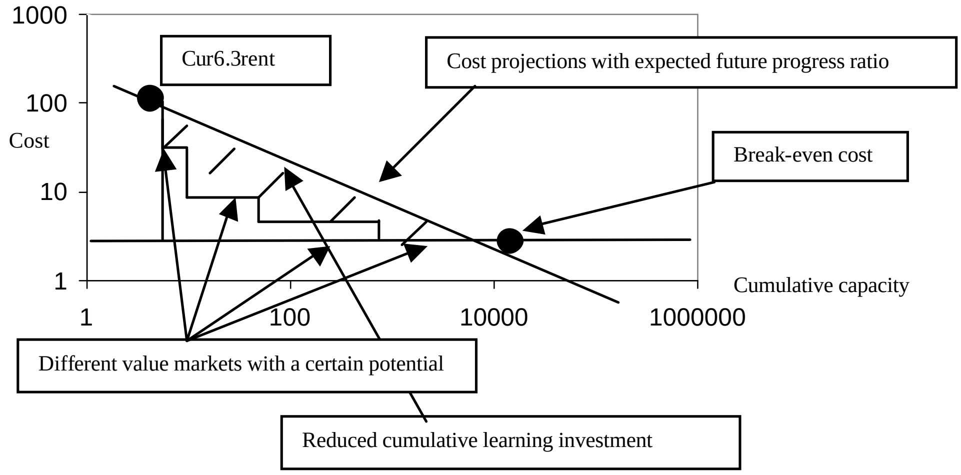

Figure 6.4 *Reducing learning investment by aiming at higher-value markets first*

Poponi et al. (forthcoming) recently have identified several of these markets. If we take Southern Italy as an example we get to the following market description:

Table 6.3 *Market characteristics for residential electricity market in the Palermo region*

Depreciation period	25
Interest rate	5%
O&M-costs (Euro2002/kWh)	0,005
Competitive price (Euro2002/kWh)	0,1978
Capacity Factor	0,173

As Poponi indicates this results in a break-even price of capital costs of about 4 Euro/Wp.

The following table summarises several results of the calculations for this case:

Table 6.4 *Break-even years, learning investments and PV market share at break-even for the case of the residential electricity market in Southern Italy*

	GR=0,1	GR=0,15	GR=0,2	GR=0,25	GR=0,3	Global cumulative learning investment (10^9 Euro)	Learning capacity (GW)
PR=0,9	2031	2021	2017	2014	2013	19	35
PR=0,85	2022	2015	2012	2010	2009	8	14
PR=0,8	2016	2011	2009	2008	2007	5	8
PR=0,75	2013	2009	2008	2007	2006	3	6
PR=0,7	2011	2008	2006	2006	2005	2	4

The shaded cells represent the calculation for the business-as-usual case (extrapolation of the past 25 years). There are several conclusions to be drawn from this table:

1. In the business-as-usual case a break-even market in the Palermo region will be reached before the end of this decade. This can be accelerated to 2005 if a high growth rate is combined with an improved progress ratio.
2. At the end of 2002 the cumulative global installed capacity was about 2.4 GW. If the remainder of the learning capacity were installed in the residential electricity sector in Southern Italy, the learning investment would be 2 to 5 billion Euro (if we exclude the PR>80% cases). This corresponds on the average to about 0.5 Euro/Wp public support. The maximum potential for this sector can be estimated roughly at 4 GW (e.g. 10 million houses with a 400 W system). With PR's better than 75%, this market could reach break-even on it's own account.
3. Since in reality almost all of the global capacity installed will be outside the Palermo region and often not in the residential electricity sector, the real learning investment will be higher. If we assume an average support of 3 Euro/Wp (i.e. about 50% of the specific system price) the learning investment needed will be between 12 billion Euro and 25 billion Euro. This means that at least in theory a saving on public support can be reached of 10 to 20 billion Euro (or about 80%) if policies were designed that would stimulate the first higher-value market with priority.

If an exhaustive list of high-value markets were available, including their maximum potentials, a detailed analysis could be made of the potential savings on learning investments by developing the higher-value markets first. Although this would be a theoretical exercise, it would indicate at least the potential of cost-saving by global collaboration on the issue of PV policy. The example above indicates this saving on learning investments costs could be in the order of 80%.

6.4 Conclusions and discussion of results

6.4.1 Investing in learning is more than RTD

The original core question of WP5 was how to strike a proper balance between RTD actions, directly aimed at technology development (a "technology push" effect) and stimulation of market penetration (a "demand pull" effect). We would like to rephrase this question in terms of how to strike a balance between the learning investments by market stimulation and investing in learning processes. In this rephrasing of the question, the definitions are:

1. learning investment (by market stimulation):
    - total amount of support spent on stimulation of market penetration up to the point of market break-even (demand pull effect).
2. investing in learning (processes):
    - total amount of support spent on technology development up to the point of market break-even. This happens not only through RTD actions but also through support of learning-by-using and learning-by-interacting processes. In more advanced learning policy also improvement of the learning processes itself (learning-by-learning) could be included. Pro-active inclusion of new actors (learning-by-expanding) could also be considered. All these actions are aimed at improving the progress ratio of a given technology.

What is clear from the literature is that both learning investment and investment in learning are important. Effective learning only takes place when both go hand in hand. However, qualitative and quantitative analysis can help to see what the possible gains are of putting more emphasis on the one or the other compared to a business-as-usual scenario.

6.4.2 Monitoring of the progress ratio very important for PV policy analysis

In the case of PV we have shown that a business-as-usual scenario with a progress ratio of 80% will be a very minimum requirement for PV to ever get to break-even in the bulk electricity market. Less favourable progress ratios will lead to prohibitive costs and required levels of penetration. Therefore substantial effort has to be put in place to keep the progress ratio at least at 80% and if possible, to instigate actions that have the effect of an improved progress ratio. Monitoring the progress ratio is therefore very important. As we have met many obstacles in the Photex project to get sufficient and reliable data, we suggest the EC takes up data collection and monitoring of progress ratios of desired technologies (such as PV) as a continuous task or supports organisations that do this.

From a scientific point of view this monitoring is also very important, if it is combined with monitoring of data regarding investments in learning. Until now data that could lead to an idea about the relation between investing in learning and the progress ratio resulting from that, are very scarce.

6.4.3 By investing in learning substantial gains on learning investments are possible

If substantial additional investments in learning processes lead to an improvement of the progress ratio of PV from 80% to 75%, there will be several benefits.

- The break-even year will come 5 tot 10 years closer.
- The market share of PV electricity needed to get to break-even will remain below the point where substantial additional cost will have to be made to account for the intermittent character of PV (e.g. storage, back-up power or improved demand response by ICT-solutions).
- The global learning investments needed to get to break-even will be reduced by several hundred billion Euros/dollars.

The latter point means that as long as the additional investments in learning (provided it leads indeed to a progress ratio of 75%) stay below the savings on learning investments, society wins also in a financial sense.

Policy makers should be aware that reduction of learning investments is not automatically accounted for in all market support policies.

It should be noted that currently there still is large uncertainty about how investment in learning and the value of progress ratios are related. Much qualitative and quantitative research in social sciences as well as in techno-economic sciences is needed to get a better idea of this relationship.

6.4.4 Estimated PV learning investment between 200 billion and 600 billion

Assuming a progress ratio between 75% and 80% in the next decades for PV, the learning investment needed to get to break-even in large bulk electricity markets can be estimated between 200 billion and 600 billion Euro/dollar. This amount may sound large, but one should realise the following things:

1. it is a global total, and thus can be shared by the large economies of the world (e.g. USA, Japan and Europe)[19].
2. it is an expenditure over 2 to 3 decades, so 7 billion to 30 billion a year on average.
3. to assess the size of such an expenditure, several comparisons can be made:
    - The total expenditure is in the same order of magnitude as
        - the GNP of a country as the Netherlands
        - 2 to 3 times the expenditure of the Iraq war and occupation
        - The annual budget deficit of the USA in 2004

[19] This statement assumes a fully efficient spillover of learning. As we have shown in previous chapters, this is nearly the case for PV modules and to certain extent for the Balance Of System.

- the average annual expenditure can be compared with
    - the monthly spending on Iraq in January 2004
    - 10% of the annual global subsidies for agriculture
    - the annual outsourcing budget of the US government
    - the cost of 300 Ariane-5 rockets
    - the value of the annual import of the non-European Mediterrean countries from Europe

4. affordable PV will drastically reduce the dependency on (foreign) oil and thus will lead to enormous cost savings on political actions related to securing oil supply to OECD nations[20].

6.4.5 …but can be reduced by a factor of 2 if external costs are taken into account

Savings on external environmental costs are not included in the analysis. According to van der Zwaan and Rabl (2003) damage avoided by PV can be estimated at 0.25 Euro/Wp (it should be noted that they stress the uncertainties of this figure). Taken this figure as a working assumption, the spreadsheet tool gives the following results:

Scenarios		BAU	Alternative 1
Progress ratio		0,8	0,75
Growth rate		0,2	0,2
Results			
Break-even outputs			
Break-even specific system costs (Euro/Wp)	0,934		
break-even year		2034	2027
total learning capacity (GW)		803	224
total learning capacity as % of current global production capacity (3300 GW)		24,3%	6,8%
Total annual learning production of electricity (TWh/yr)		1337	373
Total annual learning production as % of current global production (15000 TWh)		8,9%	2,5%
Total learning investment (billions Euro2002)		319	116
The value of investing in learning processes that improve progress ratio			
Gain on learning investment with regard to BAU case (billions Euro2002)		0	203
Annual gain on learning investment with regard to BAU case (billions Euro2002)		0	8,1

Figure 6.5 *Spreadsheet calculation results for BAU and an enhanced learning scenario taking into account avoiding environmental damage costs. Market conditions are equal to those listed in Table 6.1*

Figure 6.5 indicates that to reach the bulk electricity market total learning investments will be in the order of 100 to 300 billion Euro(dollar). This means a reduction of roughly a factor 2, if external costs are taken into account.

6.4.6 Learning investment needed can be reduced further (by a factor 2 or more) by developing high-value markets first

The example of Southern Italy in section 3.2.2. has shown that substantial reductions of learning investments are possible if high-value markets are developed first. In this theoretical case the reduction in learning investment costs was about 80%. If this were representative learning investments could be further reduced to 1 to 5 billion a year.

The Japanese PV program shows the success of an approach targeting at high-value markets. According to the PV Status report 2003 (Jäger-Waldau, 2003) the annual subsidy budget for PV is stable since 2001, while the number of systems subsidised has tripled. With a subsidy of only

[20] It should be noted that this statement implies the assumption that the transport sector will shift from oil to electricity of electricity-derived hydrogen as a transport fuel.

1 Euro/Wp (compared to the 5 to 7 Euro/Wp in Germany) the high-value residential market is developed successfully.

6.4.7 Optimal policy options based on experience curves

The best way to ensure that high-value markets for PV will be developed in the near future in Europe (and thus that the cost-effectiveness of PV policy in Europe is maximised) will be a harmonised market-based European support program for PV (e.g. based on tradable quota). One way to do this is by harmonising all Member State support programs.

However, there are good reasons not to take only optimal European cost-effectiveness as a policy target. There are several arguments why not cost-effectiveness, but for instance equal access to the possibility to invest in sustainable energy or national industry policy should be prevailing policy targets.

Therefore, three main scenarios for a harmonised policy scheme could be envisaged:

- Mass-oriented but less cost-effective solution:
  Create a Europe wide feed-in law with tariffs such that pay back time are fixed for all countries or even regions within countries. Such a programme leads to equal access to investment and stimulate as much private investment as possible. It also probably leads to a larger social acceptance with the leading idea to get more people involved.
- More cost effective solution.
  Adapt the funding for fitting to the optimum learning curve taking into account the profitability of different market segments. This solution should lead to a market change due to investment funds creation. In this case, the leading idea is business. The tool of Green Certificates for instance in combination with an European-wide obligation to consume or supply a minimum amount of solar electricity is here a better solution since it leads to only as much funding as necessary for reaching the target but the expansion goes slowly towards less cost effective areas.
- Compromise solution.
  Create harmonised feed-in tariffs with a certain level of green certificates. In this scenario, institutions investors will invest the south to make more money. This point could impact very positively the southern regions that are generally having a lower living standard. In the north, the homeowners will have their PV roof. This solution should also include room for local initiative.

6.4.8 Market support by the EU directly as a first step

As the roadmap for policy harmonisation as put forward in the Renewable Electricity Directive shows, and taking into consideration the lengthy discussions that have preceded the publication of this Directive, such a harmonisation cannot be expected in the short term. Considering that on the one hand there is a need in Member States to pursue their own policy goals and therefore have their own domestic market support programs, and on the other hand cost-effectiveness of PV learning can be enhanced substantially by focussing on high-value markets first, a market deployment support scheme by the Commission could be envisioned. Such a market-based support scheme could be based on the certificates of guarantee of origin to be installed in every Member State country by the end of 2003. It could for instance exist of a long-term tendering program for PV-guarantee certificates aimed at MS countries that do not cover yet the non-profitable gap by domestic programs.

7. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

In this chapter we will go back to the original questions and objectives. Then we will repeat the main conclusions of the different chapters. In this sense this chapter is also a kind of executive summary. We will conclude by giving a few recommendations for further research.

7.1 Recapitulation of research questions and study objectives

The question we started this report with was: *What can energy policy learn from experience curve theory?* The *approach* of the study was to tackle this question by taking PV as a in-depth study case. The *objectives of the in-depth study case* were to collect data on the PV case, to develop experience curves out of these data and to disseminate the insights derived from it. Furthermore *scientific objectives* of the study were related to the wish to develop out of the experience curve methodology a (quantitative) strategic assessment tool for energy policy and RTD policy.

Before summarising in more detail the outcome of this study in this concluding chapter, a few general remarks on the outcomes can be made:

1. Experience curve theory and methodology can be a useful tool in energy policy analysis and energy policy making. However, using experience curves in this context should be done with knowledge and much care. The approach cannot be seen as a panacea (or "Swiss Army Knife"). For example, using experience curves for policy making gives a primary focus on cost-effectiveness, but does not take into account other possible policy objectives (equity, industry policy, social acceptance etc.) that might be relevant dependent on political and cultural contexts.
2. The objectives of the case study have been met, although often with more effort than anticipated. The main difficulty was in the more difficult-than-expected gathering of data. If policy makers wish to use the experience curve approach more often, improvement of the monitoring of data and access to firm and reliable data is crucial.
3. The scientific objectives have been met to a large extent. We have learned a lot on how to deal with learning curves. These lessons have been reported in this report (Chapter 1 and 2 and summarised below). Experience curves also have been put in the larger context of learning mechanisms. More difficult it has been to develop a (quantitative) tool to assess RTD and energy policies, although some useful conclusions can be drawn. We have developed a quantitative tool that can provide insights in the discussion on the balance between "investing in learning" (RTD and support for other learning mechanisms) and "learning investments" (supporting learning-by-doing via market support programs). However, a proven quantitative relationship between investing-in-learning expenditures and the improvement of the progress ratio is still lacking. The main recommendation for further scientific research is therefore to study this quantitative relationship by a combination of qualitative (social science) and quantitative (techno-economic) research.

7.2 Contribution to the further development of experience curve methodology

7.2.1 Progress ratio can improve over time

Often it is assumed, sometimes explicitly but more often implicitly, that the progress ratio of a technology is constant over time, or if it changes, it can only increase (i.e. the learning rate deteriorates). In our analysis of PV-technology we have found to the contrary that the progress ratio has significantly improved over time. This is an important conclusion because it means that supporting technology learning by policy can be done and could be effective.

7.2.2 Conditions for the historic analysis of experience curves

We have formulated four conditions that are needed before one can sensibly make use of experience curves:

1. Sufficient, firm and reliable data should be available.
2. Choose the right system boundaries. It should be noted that systems (such as PV-systems) often consist of components that learn on different geographical scales. The systems than are compound learning systems and cannot be analysed as a whole on a restricted geographical scale.
3. Historic period of analysis should be at least 10 years, otherwise the influence of contingencies such as sudden market changes is too strong.
4. Historic period of analysis should not over represent different parts of industrial price cycles. Periods with over representation of price stabilisation periods will yield a progress ratio that is too pessimistic, whereas periods that over represent shake-out periods characterised by fast price declines will yield progress ratios that are too optimistic.

7.2.3 Recommendations for the historic analysis of experience curves

The experience we got in making experience curves had led to the following suggestions that will improve the practice of experience curve analysis:

1. *Use weighed curves*
   No single price (or cost) figure can be given for a certain year; there will always be a number of different prices that could be observed in a data set. As a result the average price for a year will usually have an uncertainty attached to it. We have found that these uncertainties can be quite significant and that they should be clearly specified. Where possible the uncertainty data should be included in the trend analysis (as weighing factors). This suggestion has the implication that the requirements for the dataset are enhanced. For every year there should be known a multiple number of primary data points. This is not always available.

2. *Identify uncertainties in trend analysis*
   Also the results from trend analysis will always have a specific uncertainty. This uncertainty should be clearly presented and included in further analyses (e.g. trend extrapolation).

3. *Use a transparent and consistent way of currency conversion*
   Currency conversions and inflation corrections can unfortunately not be avoided. Inconsistent application of such corrections may introduce a significant bias to trend analyses, especially when analysing data from a country and a period with a large fluctuation in currency conversion factor rates and/or a high inflation rate (Snik, 2002). Therefore these conversions should be done in a consistent and transparent way, starting from the nominal price data in the original currency.

   Within this study all prices are given in Euro for the year 2000. Conversion from local currency for a certain year was done by first applying the GDP deflators from that year up to 2000 and subsequently performing the conversion to euros at either the standard conversion established for Euro zone currencies or the average conversion rate for the year 2000. Furthermore all price data are end-user prices excluding taxes and subventions.

4. *Exclude data from time periods that are dominated by laboratory technology or pilot plants*
   Price and volume data from early, pre-commercial phases (pre-commercial meaning that there is no market yet, be it a self-sustaining market or a policy-driven market) in the technology development are rather uncertain. For example prices given for photovoltaic cells manufactured in a laboratory environment (i.c. early seventies) are hardly representative for prices in industrial production. Moreover, accurate data on (production) volume for these early periods are quite difficult to obtain. It has been shown that an incorrect estimate for these early data can have a very significant influence on the results of experience curve trend analyses (Snik, 2002). Therefore we recommend to exclude data from such early, pre-commercial phases.

7.3 Conclusions with respect to PV experience curves

7.3.1 Progress ratio for PV modules has improved from 80% to 77%

We have seen that for module technology, which we consider as a *global learning system*, the progress ratio has been around 0.80 if we consider the full period from 1976 to 2001. However for the last 15 years there seems to be a steeper learning curve with a PR around 0.77 or even lower. Other authors had already reported similar results (e.g. Parente et. al. 2002). From the Photex data it also appears that module prices in Germany have stabilised or even increased somewhat in the period 1999-2001.

7.3.2 BOS-progress ratio comparable to module progress ratio

A new result is that for the Balance-of-System of residential grid-connected PV systems a comparable PR of 0.80 has been realised in both Germany and the Netherlands. We have argued that BOS learning will occur mainly in a national context due to differences in building practices and codes and customer preferences. This assumption has important methodological consequences for the experience curve analysis, which can give rise to erroneous results if ignored.

The sharp BOS price reductions that we observed were not quite as expected beforehand. On the other hand, prices of inverters have shown only moderate reductions and a PR around 0.92. It may well be, however, that the *life cycle cost* of inverters have gone down more steeply because increased performance in terms of efficiency, reliability and life time. The moderate result for inverters implies that learning for non-inverter BOS (support, cabling, installation) has seen an even better Progress Ratio than 0.80.

7.3.3 Learning in BOS can be reached in different ways and can be transferred over country borders

From these results we may conclude that the policy programmes in Germany and The Netherlands, although they employed quite different approaches, both have been very successful in bringing down BOS prices for grid-connected residential PV systems. The difference was that Germany focussed on market size and the Netherlands on improvement of learning in projects of restricted size. Germany has a larger market in absolute and relative sense (and thus a larger domestic industry), but the Netherlands spent less money on a learning trajectory with the same result.

Finally we have shown that countries can learn from each other with respect to BOS development. In other words, although the BOS has its specific national aspects, BOS learning can still spill over from one country to another, be it with some delay due to necessary adaptations to the local context.

7.4 Main conclusions historical analyses policy programs

The following conclusions could be drawn from the analysis of price developments in different countries and policy contexts:

1. *There are many different national strategies*
   This is often related to geographical, cultural or political differences between the countries.
2. *Support and incentive programs cover system costs for PV in each country*
   We have seen that whatever the policy is, for the investor in one way or another in the end the system costs have to be recovered. There might be some environmentally keen people that put some of their own money in PV, but this number is limited.
3. *Steady decrease of given market support per MWp*
   Since the market support necessary to cover system costs has declined, also the market support per MWp has declined in all the countries observed.
4. *Shift from technology-push to market-pull policies*
   The expenditures for market support in some of the countries observed has been growing enormously over the last 10-15 years, whereas the R&D expenditures has remained in the same order of magnitude. This means that the balance between market support and R&D has shifted considerably in favour of the former.
5. *International spill-over in learning of Balance of System prices happens*
   Balance of System prices are different in different countries. But countries that start later with developing their markets do not start at the same high-level prices as the early-mover countries. They profit from the experience developed in these countries by making use of developed components and adapt them to their situation.
6. *BOS-prices lowest in countries with largest markets*
   As can be expected with experience, BOS-prices are lower in countries with the largest markets that started their market development earlier than other countries.
7. *Large increase in market support temporarily leads to higher module prices*
   When favourable policies are introduced this leads to a sudden increase in market size. For all countries addressed in this study, it could be observed that at this point local prices for modules increase. These short-lasting increases are observed in all countries. These increases are not occurring at the same time in the different countries and are therefore certainly related to the launching of new funding programmes.

7.5 Price projections for PV

7.5.1 Experience-curve projections and bottom-up studies

1. Experience-curve based projections better than bottom-up engineering studies
   By comparing historical bottom-up engineering price projections with historical data, and by comparing these with simple experience-curve based extrapolations, we have seen that the price projections derived from experience curves were as good/bad or better than from bottom-up engineering studies.
   It should be noticed that these experience-curve based price projections were not done under the conditions we have developed in this project as formulated in Section 7.2. This means that if experience-curve based price projections are properly done, they can give a good result.

2. Use scenarios for price projections
   Since progress ratios are not an intrinsic property of a technology, but can change over time, also the future progress ratio is unknown, as well as the future growth rate. There different scenarios, consisting of different combinations of progress ratios and growth rates should be used to make a valuable set of price projections. For PV this is done in section 7.5.2.

3. Support at least medium-term price projections with bottom-up studies
   That bottom-up engineering studies are sometimes over-optimistic about the time schedule of the realisation of cost reduction does not reduce their value in indicating how certain cost reductions can be achieved. Price projections based on experience curves can only be made credible if they are underpinned by engineering studies that show the there are sufficient possibilities to realise the mid-term (5 to 10 years) projections. For longer-term projections this becomes of course more difficult since it is unknown what kind of results and research directions can be expected in the longer-term.

7.5.2 Price scenarios for PV-systems

An example of different possible price developments of PV is illustrated in the next Figure (7.1): With a variation of PR and GR combinations several price scenarios can be developed. A scenario developed by the European Photovoltaic Industry Association (EPIA/Greenpeace, 2002) scenario is also presented as a reference scenario.

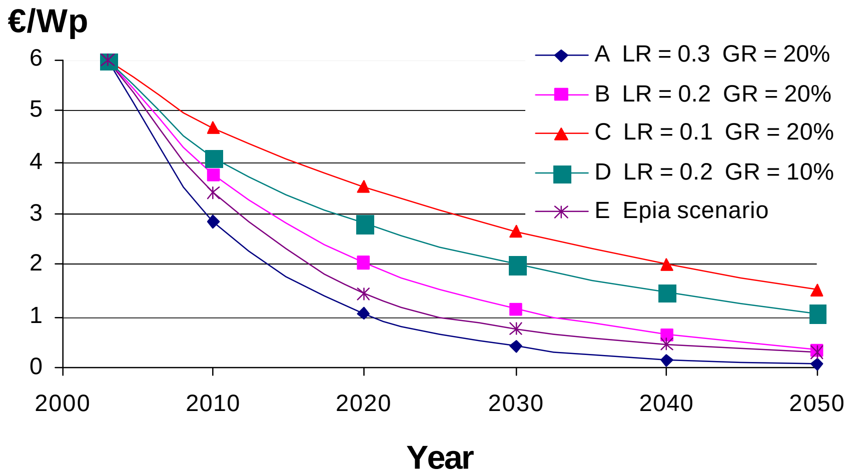

Figure 7.1 *Different price scenarios for PV-systems*

As can be seen in Figure 7.1, when an average growth rate of the annual shipments of 20% (common in the last decades) is used, a learning rate of 10% is too low to obtain low-cost PV in a reasonable time. Even with an LR of 20% the price decrease is slower than projected by EPIA/Greenpeace, unless a very ambitious implementation scheme is followed. Epia/Greenpeace extrapolated the more than 30% rates of the last five years until 2020 and could conclude that even ambitious targets are within reach.

7.5.3 Sufficient technical options for modules, inverters and BOS

With regard to modules, bottom-up studies have shown that in principle there are enough possibilities to reach a direct manufacturing cost level (i.e. costs without organisational overhead costs nor R&D-costs) of 1.15 –1.40 €/Wp for crystalline silicon and amorphous silicon technology. Critical technological factors for c-Si cost reduction are dedicated silicon feedstock processes and reduction of silicon requirements through thinner wafers and silicon sheet processes. The effect of up-scaling for c-Si technology has also been investigated, showing that the primary benefits are expected in module manufacturing, probably due to the higher degree of automation in larger plants.

SMA, the largest European inverter manufacturer has indicated that it wants to reduce inverter costs by 50% until 2006. This will be done mainly by advantages offered by mass production. They further state that cost reduction to less than € 250 per kW_{AC} does not seem possible with today's technologies. Possible breakthrough technologies leading to even lower cost inverters are complete integration of inverters with a module, high-frequency converters and high voltage converters (which need the development of high-voltage PV modules). These more radical solutions are expected to have impact after 2010.

With regard to BOS-prices a large part of the cost reduction potential seems to have been realised, at least in Germany and the Netherlands. Clue to further reduction will be further integration of components or reduction of the number of components by smarter designs. However, at least for the medium-term future, the largest part of the reduction for PV-systems has to come from reduction of the price of the modules.

7.5.4 Prices in coming decade will be influenced by many factors

The analysis above indicates that there is enough technical potential to bring costs down. However, prices will be influenced by factors not directly related to direct production costs. Three different factors that can be discussed are:

1. End of forward pricing might slow price trend down
Until now PV module producers have always indicated that instead of making profit on their module sales, they are still dealing with losses. If this is the case, this can be understood if considering that the large majority of the dominant PV-module manufacturers are relatively small departments of very large multi-national enterprises with their core businesses for instance in oil or electronic equipment. Until today these enterprises have seen their PV-businesses as a strategic investment in the future that can afford losses for some time ('forward pricing'). However, the market of PV is growing so rapidly, that the amounts of money involved start to become substantial, also for these large multinational enterprises. Remarks from industry participants during interactive sessions in the Photex-project indicate that the projected time-frame to get in black figures for the PV-departments is very close to today (2004-2005). This means that, if in the coming decade prices have to cross the cost line, the trends in prices that will be observed in the near future could be less favourable than the underlying cost trend.

2. A shortage in silicon supply might drive up PV-module production costs.
Traditionally the demand for silicon from the PV-industry has been orders of magnitude lower than demand for silicon for the ICT market The PV industry used to use waste from silicon production processes for ICT purposes as a feedstock. However, if PV continues to grow with growth rates of 15% or higher, the demand for silicon from the PV-industry will be comparable to that of the ICT industry pretty soon. Therefore PV-dedicated production processes will have to come on-line in the next few years, otherwise a supply shortage of silicon might lead to higher PV-module prices. These new production facilities will have to produce PV-silicon wafers for costs that are substantially lower than can be expected from the ICT-industry. This might be possible, because impurity levels of silicon for the PV-application can be higher than for ICT applications.

3. Possible overcapacity in case of lower demand
Because of the soaring demand of the last few years, many PV module producers are expanding their production capacity rapidly (while sometimes closing down smaller and older production locations). In case the current growth rates of about 30% are not maintained (which is a probable

assumption), possibly a production overcapacity might develop. In that case prices in the market will come under pressure.

7.6 Investing in learning and learning investments

7.6.1 Investing in learning is more than RTD

The original core question of WP5 was how to strike a proper balance between RTD actions, directly aimed at technology development (a "technology push" effect) and stimulation of market penetration (a "demand pull" effect). We would like to rephrase this question in terms of how to strike a balance between the learning investments (market support) and investing in learning (policy programs aiming at improving the progress ratio). What is clear from the literature is that both learning investment and investment in learning are important. Effective learning only takes place when both go hand in hand. However, qualitative and quantitative analysis can help to see what the possible gains are of putting more emphasis on the one or the other compared to a business-as-usual scenario.

7.6.2 Monitoring of the progress ratio very important for PV policy analysis

In this project a spreadsheet tool has been developed that can calculate the effects of different scenarios in terms of different combinations of progress ratios and growth rates. In the case of PV we have shown that a business-as-usual scenario with a progress ratio of 80% and a growth rate of 20% will be a very minimum requirement for PV to ever get to break-even in the bulk electricity market. Less favourable progress ratios will lead to prohibitive costs and required levels of penetration. Therefore substantial effort has to be put in place to keep the progress ratio at least at 80% and if possible, to improve it. Monitoring the progress ratio is therefore very important. As we have met many obstacles in the Photex project to get sufficient and reliable data, we suggest the EC takes up data collection and monitoring of progress ratios of desired technologies (such as PV) as a continuous task or supports organisations that do this.

From a scientific point of view this monitoring is also very important, if it is combined with monitoring of data regarding investments in learning. Such monitoring could lead to a better understanding of the qualitative relationship between investing in learning and the progress ratio. Until now data that could lead to an idea about the relation between investing in learning and the progress ratio resulting from that, are very scarce.

7.6.3 By investing in learning substantial gains on learning investments are possible

If substantial additional investments in learning processes lead to an improvement of the progress ratio of PV from 80% to 75%, there will be several benefits. The break-even year will come 5 tot 10 years closer. The market share of PV electricity needed to get to break-even will remain below the point where substantial additional cost will have to be made to account for the intermittent character of PV (e.g. storage, back-up power or improved demand response by ICT-solutions). The global learning investments needed to get to break-even will be reduced by several hundred billion Euros/dollars.

The latter point means that as long as the additional investments in learning (provided it leads indeed to a progress ratio of 75%) stay below the savings on learning investments, society wins also in a financial sense.
It should be noted that currently there still is large uncertainty about how investment in learning and the value of progress ratios are related. Much qualitative and quantitative research in social sciences as well as in techno-economic sciences is needed to get a better idea of this relationship.

7.6.4 The value of high-value markets

Substantial reductions of learning investments are possible if high-value markets are developed first. The success of an approach targeting at high-value markets first is shown by the Japanese

PV program. According to the PV Status report 2003 (Jäger-Waldau, 2003) the annual subsidy budget for PV is stable since 2001, while the number of systems subsidised has tripled. With a subsidy of about 1 Euro/Wp the high-value residential market is developed successfully.

7.6.5 Optimal policy options based on experience curves and the option of direct EU-support

The best way to ensure that high-value markets for PV will be developed in the near future in Europe (and thus that the cost-effectiveness of PV policy in Europe is maximised) will be a harmonised market-based European support program for PV (e.g. based on tradable quota). One way to do this is by harmonising all Member State support programs. However, there are good reasons not to take only optimal European cost-effectiveness as a policy target. There are several arguments why not cost-effectiveness, but for instance equal access to the possibility to invest in sustainable energy or national industry policy should be prevailing policy targets. As national policies take these policy targets into account there could be a case for a market deployment support scheme by the Commission directly. Such a market-based support scheme could be based on the certificates of guarantee of origin to be installed in every Member State country by the end of 2003.

7.7 Recommendations for further research

7.7.1 Support data monitoring to be able to make valuable experience-curve based analyses

If policy makers want to make use of experience curve theory based policy analyses, it is in their interest that these analyses are done with sufficient care and under the conditions mentioned in sections 2.2 and 7.2. To meet these conditions, it is necessary that data on prices, volumes and policy programs in different countries are better available. The work of branch organisations or IEA Annexes or Working Parties in this area can be highly valuable in this respect. With respect to PV we suggest the Photex database can serve as a good starting base and should be kept alive and updated regularly.

7.7.2 Support research on empirically proven quantitative relationship between investing-in-learning and learning investments

Empirically-based research on getting a better feeling for the quantitative relationship between investing in learning and the progress ratio is completely lacking. The only studies done on such a quantitative relationship are modelling studies (the sequence of TEEM-Sapient-Sapientia projects) that assume a certain causal model (the two-factor learning curve) and use R&D statistics to determine the parameters of this model. We would suggest to put more effort on determining a causal model on an empirical basis and use this as a start to determine relationship between investing in learning and learning investments. Such research should be a combination of qualitative/social science research and quantitative analyses.

7.7.3 Studies on high-value markets

High-value niche markets can be good and cost-effective learning grounds for technologies in development. From a European perspective also enormous cost gains can be realised if high-value markets are developed first. Therefore publicly available European-wide and possibly world-wide study on where early grid-connected markets are for PV will be helpful for policy makers to show this potential. Public knowledge on these high-value markets can also improve the competitiveness in the industry as it as valuable information for industrial parties that are considering entering the PV sector.

8. REFERENCES

1. Alonso et al., Alonso, J., Bruton, T.M. Woodcock, J.M. Royk, K, Garrad, B., Nijs, J. Räubler, A., Valléra, A., Schade, H. Alsema, E., Hill, R. and Dimmler, B., *Multi-Megawatt Scale-up of Silicon and Thin-Film Solar Cell and Module Manufacturing (MUSIC-FM), APAS RENA CT94 0008*, European Union, Brussels, 1997.

2. Argote, L., and Epple, D. Learning Curves in Manufacturing, in *Science*, Vol. 247, pp. 920-924, February 1990

3. Bruton, T.M., Music FM, five years on fantasy or reality? paper presented at conference *PV in Europe*, Rome October, 2002.

4. Criqui et al, 2000, Criqui, P., Martin, J-M., Schrattenholzer, L., Kram, T., Soete, L., and van Zon, A., Energy Technology Dynamics, in *International Journal on Global Energy Issues*, Vol. 14, no. 1-4, 2000.

5. ECN (2003) Renewable Electricity in Europe Fact sheets: The Netherlands 2003 www.renewable-energy-policy.info/relec/netherlands/policy/investment

6. EPIA/Greenpeace, Solar Generation; solar electricity for over 1 billion people and 2 million jobs by 2020, ISBN 90-73361-77-x, Brussels/Amsterdam, 2002.

7. EurObserver, PV-Barometer, in *Systemes Solaires*, no 154, April 2003.

8. Frantzis, L., Jones, E., Opportunities for cost reduction in photovoltaic modules, in *Proceedings of the 16th European Solar Energy Conference*, Glasgow, 2000.

9. Harmon, C., *Experience curves of Photovoltaic Technology*, Interim Report, IR-00-014, International Institute for Applied Systems Research IIASA, Laxenbourg, 2000.

10. IEA, 2000 International Energy Agency, 2000. *Experience curves for energy technology policy*, OECD/IEA, Paris, France.

11. IEA, 2002. Renewables information 2002 - with 2000 data, OECD/IEA, Paris, France.

12. IEA, PVPS 2002, Trends in Photvoltoic Applications in selected IEA Countries between 1992 and 2001, Report IEA-PVPS T1 - 11 : 2002.

13. Jäger-Waldau, A., 2002. *Status of PV Research, Solar Cell Production and Market Implementation in Japan, USA and the European Union*, European Commission, DG JRC, EUR 20245 EN, September 2002.

14. Jäger-Waldau, A., 2003. *Status of PV Research, Solar Cell Production and Market Implementation in Japan, USA and the European Union*, European Commission, DG JRC, September 2003.

15. Kamp, L.M. (2002), *Learning in wind turbine development: a comparison between the Netherlands and Denmark*, Dissertation Utrecht University

16. Kouvaritakis, N. A. Soria, S. Isoard (2000), Modelling energy technology dynamics: methodology for adaptive expectations models with learning by doing and learning by searching, *Int. J. Global Energy Issues*, Vol. 14, Nos. 1-4, pp. 104-115.

17. Kram, T., A.J. Seebregts, G.J. Schaeffer, L. Barreto, S. Kypreos, S. Messner and L. Schrattenholzer (2000), Technological dynamics in energy systems models with perfect foresight, *Int. J. Global Energy Issues*, 14, 1-4, 48-64.

18. Mattson, N. (1997): Internalizing technological development in energy system models. Thesis for the degree of licentiate in engineering, Chalmers University of Technology, report ISRN CTH-EST-R--97/3--SE, Göteborg, Sweden, November 1997.

19. Mattson, N. and C.-O. Wene (1997): Assessing new energy technologies using an energy system model with endogenized experience curves. *Int. J. of Energy Res*., Vol 21, 385-393, 1997.

20. Meinhardt, M. and Cramer, G. 'Cost Reduction of PV inverters - Targets, paths and limits'. In, Proceedings of the *17th European Photovoltaic Solar Energy Conference, Munich, Germany*. 2001

21. Messner, S. (1997): Endogenized technological learning in an energy systems model. *J. Evol Econ*, 7: 291-313, September1997

22. Mierlo, B. van, 2002, *Kiem van maatschappelijke verandering. Verspreiding van zonnecelsystemen in de woningbouw met behulp van pilotprojecten*, PhD-thesis University of Amsterdam, 2002

23. Mikita, A., L. Schrattenholzer (2002), Optimizing R&D expenditures on energy technologies using a stylized energy supply model, Draft submitted 15 October 2002 to *Energy Policy*.

24. Neij, L, (1997): Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology. *Energy Policy*, Vol. 23, No. 13, pp. 1099-1107, 1997.

25. Neij, L., Andersen PA, Durstewitz, M, Helby, P, Hoppe-Klipper, M, Morthorst, P, *Experience Curves: A Tool for Energy Policy Assessment*, Department of Technology and Society, Lund University, 2003.

26. Noord, M. de, L.W.M. Beurskens, H.J. de Vries, 2003. *ECN data set on renewable energy sources*, ECN-C-03-006, ECN, Petten, the Netherlands, November 2003 (in preparation).

27. Parente, V., J. Goldemberg, R. Zilles, 2002. Comments on Experience Curves for PV Modules, *Prog. Photovolt: Res. Appl*. 2002; 10:571-574.

28. Poponi, D., 2003, Analysis of diffusion paths for photovoltaic technology using experience curves, in *Solar Energy*, Vol. 74, p.331-340, 2003

29. Poponi D., Byrne J, Hegedus S., *Analysis of cost-reduction potential for photovoltaic technology* (forthcoming)

30. Rotmans, J. and and Kemp, R 2003, Managing Societal Transitions: Dilemma's and Uncertainties: The Dutch Energy Case Study, paper presented at the OECD Workshop

on the benefits of Climate Policy: Improving Information for Policy Makers, 12 September 2003

31. Seebregts, A.J., T. Kram, G.J. Schaeffer, A.J.M. Bos (2000), Endogenous learning of technology clusters in a MARKAL model of the Western European energy system, *Int. J. Global Energy Issues*, 14, 1-4, 289-319.

32. Snik, A. *Experience Curves for Photovoltaic Energy Technology*, Report NWS-E-2002-20, Dept. of Science, Technology and Society, Utrecht University, 2002

33. Strategies Unlimited, *Five-Year Market Forecast*, *2002-2007*, report PM-52, March 2003

34. Vries, H.J. de; Roos, C.J.; Beurskens, L.W.M.; Kooijman-van Dijk, A.L; Uyterlinde, M.A., *Renewable electricity policies in Europe: Country fact sheets 2003*, ECN-C--03-071, October 2003

35. Williams, R.H., Terzian, G., A *Benefit / Cost Analysis of Accelerated Development of Photovoltaic Technology*, PU/CEES Report no. 281, Center for Energy and Environmental Studies, Princeton University, 1993.

36. van der Zwaan, B.C.C. and A. Rabl, “Prospects for PV: a learning curve analysis”, *Solar Energy*, vol.74, no.1, 19-31, 2003.

37. van der Zwaan, B.C.C. and A. Rabl, “The learning potential of photovoltaics: implications for energy policy”, *Energy Policy*, 32, 13, 2004, pp. 1545-1554.

9. LIST OF ABRREVIATIONS

Abbreviation	Meaning	Remark
BAU	Business As Usual	
BIPV	Building Integrated PV	
BOS	Balance of System	BOS-price = system price minus module price
EPIA	European Photovoltaic Industry Association	
EU	European Union	
GC	Global Capacity	
GR	Growth Rate	
ICT	Information and Communication Technology	
IEA	International Energy Agency	
LR	Learning Rate	Complement to Progress Ratio LR = 1- PR
MW	Megawatt	
PR	Progress Ratio	
PV	Photovoltaic	
R&D	Research and Development	
SU	Strategies Unlimited	US consultancy company
UPS	Uninterruptible Power System	
Wp	Watt peak	The unity of power delivered by a PV module at the moment of peak production

APPENDIX A STRUCTURE OF THE PHOTEX DATABASE

The project partner ISET has set up the database. ISET uses an Oracle® server which contains data of numerous projects and applications. Special tables have been created for the PHOTEX project inside this database. An interface allows to import/export the data to and from an identical database in Microsoft Access format. This database is accessible at a special ftp-internet site, protected by a password procedure. This structure has allowed to establish an easy possibility of exchanging data with the project partners.

The database exists out of three data tables: PHOTEX_TAB, ECON_INDICATOR_TAB and EUR_CONV_TAB. The information stored in these main tables is defined in the following way.

- The table PHOTEX_TAB keeps three different data categories which can be divided in physical data, market data and other data. This is in principal the core table of the database where all available information about PV systems is stored. PHOTEX_TAB contains about 3,600 records at present.
- The table ECON_INDICATOR_TAB is compiled of annual economic key figures for relevant countries which are necessary for experience curve calculations e.g. GDP-deflator or of other special interest e.g. US Dollar exchange rate. ECON_INDICATOR_TAB holds a total of about 700 records from 25 countries between 1974 and 2002 at present.
- The table EUR_CONV_TAB contains information on official exchange rates of national currencies to the Euro. The data is used to calculate comparable prices in a reference currency,. e.g. Euro. EUR_CONV_TAB keeps conversion rates of 18 countries at present, so table size is 18 records.

Due to the relational structure of the database all information of the tables can be combined with each other using their cross reference entries. The layout of the data base is shown in the next Figure.

Figure 9.1 *Table structure and layout of PHOTEX data base*

All relevant and available information about individual PV installations, economic data etc. and components are stored in the data records.