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The Way to Competitiveness of PV -
An Experience Curve and Break-even Analysis

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Zusammenfassung

Erfahrungskurven beschreiben die Abnahme der Stückkosten eines Produktes im Verhältnis zur Steigerung der kumulierten Produktionsmenge. Dieses Konzept wird verwendet, um die Preissenkungen der Photovoltaik (PV) in der Vergangenheit zu untersuchen und die möglichen ökonomischen Auswirkungen von verschiedenen PV Wachstumsszenarien zu bewerten. Auf der einen Seite ist es Ziel der Dissertation zu zeigen, wie PV Erfahrungskurven konstruiert werden müssen, damit alle Preissenkungen erfasst werden – nicht nur diejenigen der Investitionskosten –und welche Auswirkungen sich für die progress ratio daraus ergeben. Auf der anderen Seite soll untersucht werden, welche Lerninvestitionen notwendig sind, damit die PV die wirtschaftliche Wettbewerbsfähigkeit für die Stromerzeugung erreicht, und welche Gewinne durch die Photovoltaik im Strommix entstehen werden.

Im ersten Schritt wird die vorhandene PV Erfahrungskurvenliteratur kurz besprochen und die Ergebnisse der Studien erörtert. Im zweiten wird hervorgehoben, wie wichtig es für die Erfahrungskurvenanalyse ist, neben den Investitionskosten weitere Faktoren wie z.B. Systemlebensdauer oder performance ratio mit einzubeziehen. Verschiedene Datenquellen für die Konstruktion von PV Erfahrungskurven werden bewertet und die Herausforderung von globalem und lokalem Lernen wird erörtert. Die Ergebnisse der konstruierten Erfahrungskurven auf Basis von Modul-, System- oder kWh-Preisen werden ausgewertet. In einem dritten Schritt werden die Lerninvestitionen verschiedener Szenarien analysiert. Durch die Kombination von Preisdaten der Strombörse mit Erzeugungsprofilen von PV Systemen mit mehr als 10 MW Leistung wird der Wert der PV im öffentlichen Stromnetz ermittelt. Das break-even Modell simuliert die Kombination verschiedener Szenarien für das PV Wachstum, für die PV Preissenkungen, für den Preisanstieg des herkömmlichen Strompreises und für verschiedene Diskontierungsmethoden sowohl auf einer weltweiten Basis als auch aus dem Blickwinkel der deutschen Wirtschaft. Diese Ergebnisse werden in einem Szenario für einen stark exportorientierten deutschen Markt und einem Szenario der schnellen PV Verbreitung in globalen Nischenmärkten erweitert. Basierend auf diesen Erkenntnissen schließt die Dissertation mit Folgerungen, die sich für die Energiepolitik ergeben.

Abstract

Experience curves describe the decline of costs of a produced unit with increased cumulative production. This concept is used to research past price decreases in photovoltaics (PV) and to evaluate the potential economic impact of different PV growth scenarios. On the one hand this thesis aims to show how the PV experience curves must be constructed to include all price decreases, not only investment costs, and how this affects the progress ratio of PV. On the other hand it aspires to investigate which investments are necessary to reach the competitiveness of PV for electricity power production and which profits will occur through the use of PV in the electricity mix.

Firstly, the literature of PV experience curves is briefly reviewed and the results of the studies are discussed. Secondly, the relevance of including other factors; not only the investment costs in an experience curve analysis are highlighted (e.g. change of system lifetime or performance ratio). Different data sources for the construction of PV experience curves are evaluated and the challenge of local and global learning is discussed. The results of the constructed experience curves based on module, system or kWh price basis are interpreted. Thirdly, in the break-even analysis section, learning investments of different scenarios are analysed. The value of PV in the public electricity grid is derived from the combination of power exchange price data with more than 10 MW PV systems production profiles. The break-even model simulates combinations of different scenarios for PV growth, PV price reduction, electricity price increase and discounting methods on a worldwide basis as well as from the point of view of the German economy. These results are enhanced with a scenario for a German market which is particularly export orientated and a scenario for the fast introduction of PV in global niche-markets. Based on these insights, the thesis concludes with consequences which emerge for energy policy.

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Abbreviations

BEP	Break-even Price
Bn	Billion
BOS	Balance of System
Cap	Capacities
CDM	Clean Development Mechanism
CO_2	Carbon Dioxide
cum	cumulative
D	Germany
DCF	Discounted Cash Flow
disc	discounted
$	Dollar
EEG	Erneuerbare Energien Gesetz (Renewable Energy Law of Germany)
EEX	European Energy Exchange
EU	European Union
€	Euro
GW	Gigawatt
Inv	Investment
KfW	Kreditanstalt für Wiederaufbau
kWh	Kilowatt-hour
kWp	Kilowatt peak
LR	Learning Rate
MWp	Megawatt peak
n.a.	not available
NPV	Net Present Value
O&M	Operation and Maintenance
POP	Point of Profit
PR	Performance Ratio or Progress Ratio
PV	Photovoltaic
t	Tons
yr	Year

1 Introduction

1.1 Motivation

The problems with our current energy system are widely visible: These are the destruction of the climate and environment through CO_2 and other emissions, danger of terrorist attacks and unsolved problems concerning nuclear power as well as increasing prices through exploding energy demand in countries such as India and China and limited resources, etc.. Therefore within society there exists a great desire for an environmentally-friendly, secure and economically affordable energy source. Energy production with Photovoltaic (PV) Power has many advantages from the environmental perspective, for example; no air pollution during operation, no waste problems, etc. and could contribute, in conjunction with other renewable energy, an important portion to the energy mix. But the photovoltaic share in the electricity mix is still very small (less than 0,5% worldwide [Maycock 2005];[EWI/Prognos 2005]), because the PV kWh price is still relatively more expensive than the sale price of nuclear or fossil electricity.

The technology of PV is still very young and the cumulative capacities produced so far are dimensions below other energy technologies. This opens possibilities for price reductions with accelerating mass production. The phenomena of decreasing prices with increasing cumulative production output can be described with the experience curve methodology. In a break-even analysis the results of experience curves research are projected into the future. This makes it possible to estimate learning costs and profits from introducing PV into the energy mix.

1.2 Objectives of Study

This thesis aims to develop a greater understanding of past price decreases of PV and the potential economic impact of an increased PV use for electricity production.

In the experience curve section the current literature is reviewed and evaluated. It is shown that most studies rely only on the module or system price. This disregards other variables which have an influence on the price of a PV kWh like system lifetime, performance ratio, degradation of energy earnings, yearly variable costs, inflation or imputed interest (in this work they are called soft factors). For the competitiveness of PV the price of a kWh is critical, not only the investment price.

Hence the main aims for the experience curve section are:

- The test of the sensitivity of the PV kWh price when improving soft factors,
- The construction of different types of PV experience curves to compare the results of using only module price data or using PV system price data or using PV kWh price data,
- The analysis of the question of the adequate cumulative reference,
- The implications for the extrapolation of kWh based experience curves in a break-even analysis.

The second part of the work deals with the future of PV. It demonstrates in different scenarios, what costs or profits will occur through an increased use of PV. The economic impact of PV is very much influenced by the value of the electricity in the public grid which PV can replace. The discussion about this topic has started in recent years and this work aims to contribute with a detailed analysis of hourly based PV production profiles combined with electricity price profiles of the European Power Exchange (EEX). Using these results and those of the experience curve section a break-even model will be developed which is able to simulate scenarios for the global and the local market depending on different growth rates of PV, progress ratios of PV and the development of the break-even prices. Special importance will be paid to the question of how to discount future cash flows. The break-even analysis will be completed with the discussion of two special scenarios: Firstly, a strong export orientated strategy of the local German market is presented to demonstrate the influence on the local learning investments of Germany. Secondly, the economic advantages of using the niche-market of mini-grids, which has a comparatively higher break-even price, are researched.

The principal goals in the break-even analysis section can be summarised as follows:

- Analysing price profiles of the EEX and PV production profiles,
- Discussion of external costs of power generation,
- The development of a break-even model for PV,
- Pointing out the different possibilities of discounting and their influence,
- Analysing learning investments and possible profits for different global and local scenarios,
- Evaluation and comparison of alternative scenarios: export orientation of the German market and niche-market mini-grids.

1.3 Outline of the Dissertation

Chapter 1 presents the motivation and the objectives of the study. Chapter 2 presents the principal concept of experience curve theory and the literature overview of research in the field of PV experience curves. Chapter 3 gives a description of the soft factor variables and their influence on the PV kWh price and presents the data collection and construction of different experience curves. Chapter 4 deals with the value of PV in the public grid and describes the break-even model. It also includes the evaluation of necessary learning investments and possible profits of PV growth scenarios. Conclusions and recommendations are made in Chapter 5. References are given in Chapter 6.

2 PV Experience Curves Overview

In the first part of this chapter a brief introduction about the experience curve theory is given. In the second part the use of photovoltaic experience curves in literature is illustrated. This includes a summarisation and discussion of the results of the most important studies undertaken so far.

2.1 Concept of Experience Curves

The concept of experience curves describes how costs of a produced product unit decline with increased cumulative production. The observation is quite old and was documented e.g. by Wright in 1936 who described the decrease of labour costs in airframe manufacturing [Williams et al. 1993]. Sometimes it is differentiated between learning curves (analysing only one factor) and experience curves which include costs for research, administration, marketing and capital. The second ones relate therefore to the total costs and cumulative production analysing a complete market and are used in this work.

2.1.1 The Experience Curve Formula

The specific characteristic of an experience curve is the constant percentage of decline of the costs with each doubling of the cumulative production. Therefore the experience formula can be described as:

$$\mathrm{Cost}(x) = a * x^m$$
$$\log(\mathrm{Cost}(x)) = \log a + m * \log x$$

where

Cost(x)	Cost of unit x
x	cumulative (unit) production
a	Cost of the first unit produced
m	experience (or learning) index, which is constant

The Parameter m is normally negative and is used to calculate the progress ratio (PR) and the learning rate (LR):

$$PR = 2^m$$
$$LR = 1 - 2^m$$

The progress ratio also measures the relationship between the increase in cumulative production and the decrease of unit costs. A progress ratio of 80% which is equal to a learning rate of 20% means, that each doubling of cumulative production costs decreases 20%.

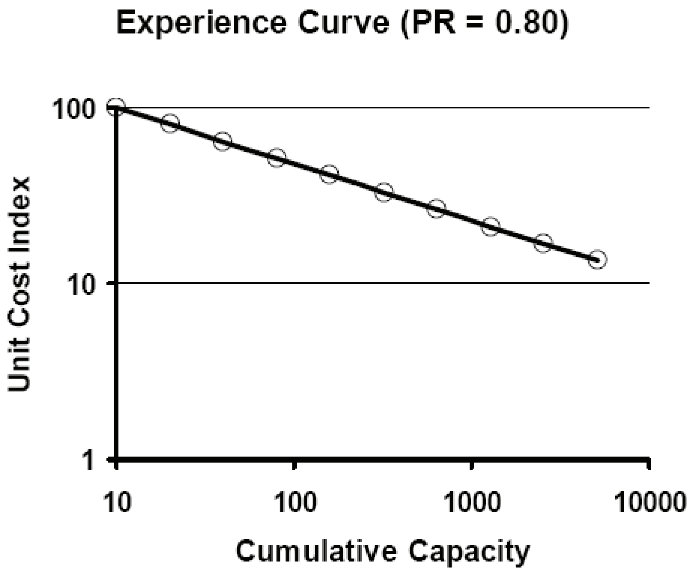

Figure 2-1: Example of an experience curve[1]

2.1.2 Types of Experience Curves

Cost or price experience curves?

In principle experience curves can be constructed on a cost or price basis. Using cost data of the production process seems the more appropriate way, but this data is very difficult to obtain and even more difficult to trust. Companies are not really interested in publishing their cost structure for competitive reasons.

Using price data from official publications or past trades, that took place, is a good alternative. In stable markets the price experience curve will be a parallel line above the cost experience curve which is caused by the price margin. In practice stable markets with constant price margins do not always exist and therefore the price experience curve can have some discontinuities. [IEA 2000] describes this effect in his publication (see section 2.2.1). But the competition of market participants is responsible for lowering increased price margins through the attraction of new competitors and also for increasing a small price margin again, when competitors do not survive. Therefore over a long time the average of the price margin does not change a lot and the results from price data are as viable as from cost data. For the break-even price analysis price experience curves are even more adequate because official price data of public power exchanges can be used and we do not have to rely on cost data of other energy sources. These are the reasons why in this work price experience curves are used.

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[1] Source: [Schaeffer et al. 2004a]

References for cumulative capacities:
When talking about experience curves and comparing results special attention has to be paid to the used references. PV experience curves can be categorised in different types as follows:

I. price per kW vs. cumulative number of installed/produced kW
II. price per kWh vs. cumulative number of installed/produced kW
III. price per kWh vs. cumulative number of produced kWh

As it can be seen in the following literature overview, type I curves are most widely used. Type II curves have not been researched a lot so far and therefore are one of the main targets of this thesis. Between type II and III there are not really any new insights, but type III may be preferred to compare PV to other energy technologies.[2]

2.2 PV Experience Curves in the Literature

In recent years an increase of literature on experience curve theory for energy technology can be noted. Before the year 2000 there were only very few published studies of PV experience curves (e.g. [Williams et al. 1993];[Neij et al. 1997]). Hereafter the most important recent publications on PV experience curves are summarised. The numbers of the studies can also be found in overviews in Table 2-1 and Table 4-3. The summarisation does not intend to give a complete résumé of the studies but concentrates on the aspects that are relevant to this work: PV experience curves in the past and break-even scenarios for the future price development of PV. Not all studies deal with both topics (studies with only break-even price aspects are described in section 4.2).

2.2.1 [IEA 2000]

This study is a very comprehensive piece of work about experience curves and their relevance for energy technology policy. It therefore not only deals with PV experience curves but includes this topic as well.

In the first part of the work ("Riding on the Experience Curve") the author describes with the example of PV how the cumulative break-even capacity and the corresponding learning investments are calculated. Assuming a break-even price of 0,5 \$/Wp and a progress ratio of 80% for the PV modules a cumulative production of 200 GW is required which corresponds to 60 billion US\$ worth of learning investments. Although the author mentions an experience curve for PV on kWh basis with a progress ratio of 0,65 he found in the literature, he agrees that, this is not more

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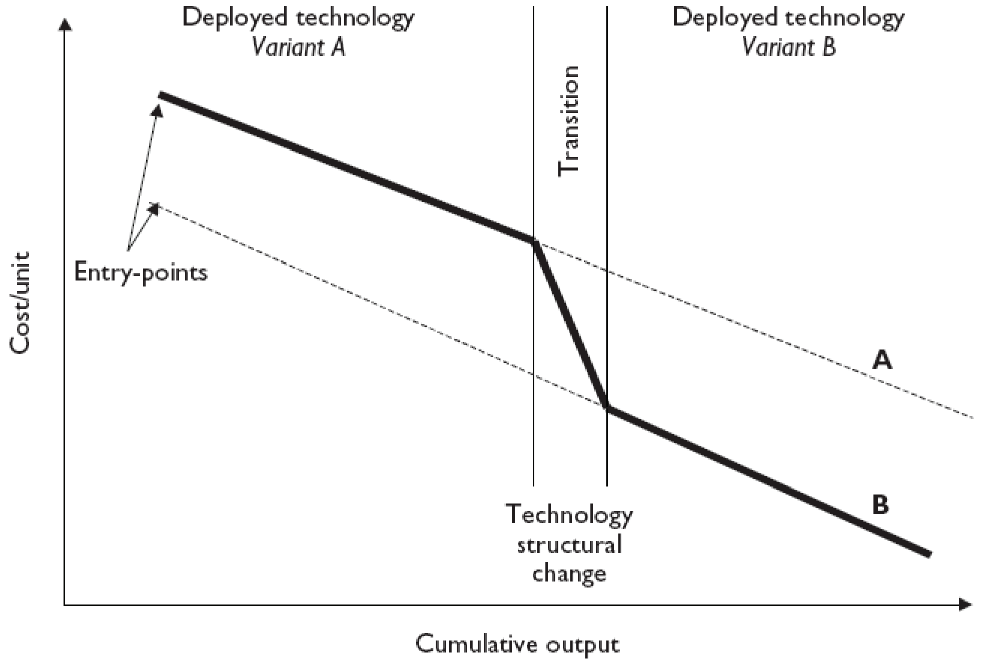
[2] In this work no comparisons between PV and other energy technologies experience curves are made. Therefore the work concentrates on type I and type II experience curves.

than a “very rough estimate”, because it was constructed of only 3 data points at five-year intervals and without differentiating between stand-alone and grid-connected PV systems (therefore it is not mentioned in Table 2-1).

In the second part a closer look is taken at changes or interruptions that can occur in the construction of experience curves. A so called “technology structural change” takes place, if major technical shift in the production process lets the experience curve jump from the old technology variant A (e.g. crystalline PV) to the new technology variant B (e.g. thin-film PV). The two technology variants may have the same progress ratio, but during the transition period there is a significantly higher progress ratio (see Figure 2-2).



The heavy line is the expected behaviour of the experience curve during a shift of technology from variant A to variant B.

Figure 2-2: Technology Structural Change[3]

In figure Figure 2-3 a market structural change can be seen. First the producer sets the price below the costs, then during the so called “Price Umbrella” period he profits from decreasing costs but maintains the high price until the “Shakeout” period, caused, for example, by new market entrants and competitors. The price decreases faster than costs and stabilises finally at the same progress ratio, like the costs. For the PV module market in the EU from the year 1976-1996 the author gives a

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[3] Source: [IEA 2000]

progress ratio of 84%. Around 100 MW cumulative capacity he finds a structural break with a progress ratio of 53% and afterwards the progress ratio stands at 79%. The author concludes that cost and price experience curves can differ sometimes, but in the long run they always come back to the same average progress ratio due to competition among market participants.

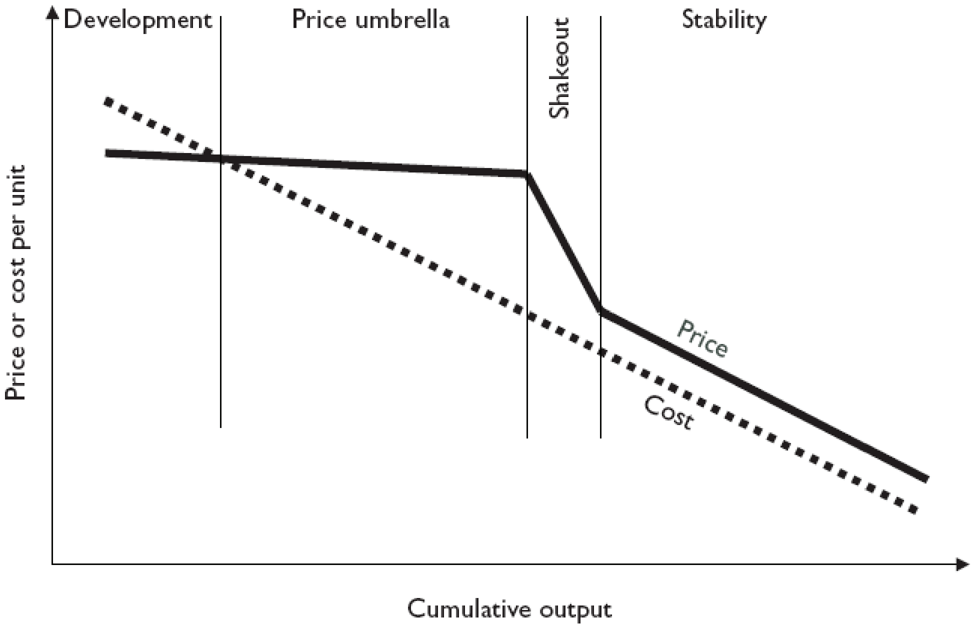

Figure 2-3: Market Structural Change[4]

In the third part a seminal paper from Tsuchiya is quoted, where the prospects for Japanese niche-markets are analysed. Without niche-markets the BEP of ca. 10 Yen/kWh would be reached at a cumulative installed capacity of more than 100 GW for a progress ratio of 76%. But assuming niche-markets (situations where customers are willing to pay more for PV energy, because it is used for certain purposes where other energy sources are also more expensive, e.g. rural electrification, no emissions during operation) BEPs are different for each market. Depending on the volume and BEPs of the single niche-markets a decreasing BEP-line is constructed which reduces the necessary cumulative capacity to 6 GW for a progress ratio of 76%. On arrival at this cumulative capacity a self-sustaining PV-Market is reached and the learning investments further on will be made by this market, without public support.

In the fourth section the author gives the main results of a BEP study he made the year before. Assuming a progress ratio of 79% learning investments could reach the undiscounted sum of 150 billion US$ from 2000 to 2013 while the present value of

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[4] Source: [IEA 2000]

PV for the years 2000-2030 is positive: about 300 billion US$. Making the simulation with 3 different technologies (including biomass liquefaction and electricity or heat from biomass) the present value is only 15 billion US$, because all three technologies compete for the same learning opportunities.

Discussion:
Regarding the PV part of the paper the numbers given by the author are difficult to verify, because he quotes a lot of workshop and seminal papers. But nevertheless the approach of using niche-markets seems very interesting and goes in the same direction as one part of the break-even analysis of this work (see section 4.5.2). The assumption in the last part, that different renewable technologies compete for the same learning opportunities and learning investments is, in my opinion, untrue. On the contrary, renewable energies mostly compete with nuclear power (also nuclear fusion) for CO_2 reasons and therefore can be researched independently from one other. Learning investments in one renewable energy technology do not necessarily reduce the possibility of learning investments in other renewable energy technologies.

2.2.2 [Harmon 2000]

In his paper, Harmon wants to present "the longest experience curve for PV systems assembled to date". Without collecting own data an experience curve of module prices from 1968-1998 is constructed with price data from [Maycock et al. 1975];[Thomas et al. 1999];[Watanabe 1999]. Early progress regarding worldwide installed module capacity shows more than 13 cumulative doublings, yet the reliability of a progress ratio of 78,8% is questionable. Even in 1976, cumulative installed capacity was found to be extremely small: at under 1 MW. Because of missing data for BOS, there are no numbers given for BOS experience curves, just a few examples of price reductions are mentioned in this part of the paper. Neither the question of break-even prices nor learning investments are assessed.

Discussion:
Although quite often quoted in literature this paper does not really offer new consolidated findings of PV experience curves, but combines research that was done before to one long experience curve. Because of the non-industrialised production methods before 1976 it is questionable, if this long experience curve really makes sense.

2.2.3 [Parente et al. 2002]

This publication updates the experience curve for PV modules based on price data from Maycock until the year 2000. Excluding the years before 1981, because of unreliable data in the opinion of the authors, a progress ratio of 77,2% for the years 1981-2000 was found. After splitting this curve into two separate ones from 1981-1990 and 1991-2000 a Chow structural break test identifies the statistical relevance and proves that these two new curves represent a better adjustment. The decrease of the progress ratio from 79,8% in the eighties to 77,4% in the nineties leads to lower future learning investments than expected, conclude the authors.

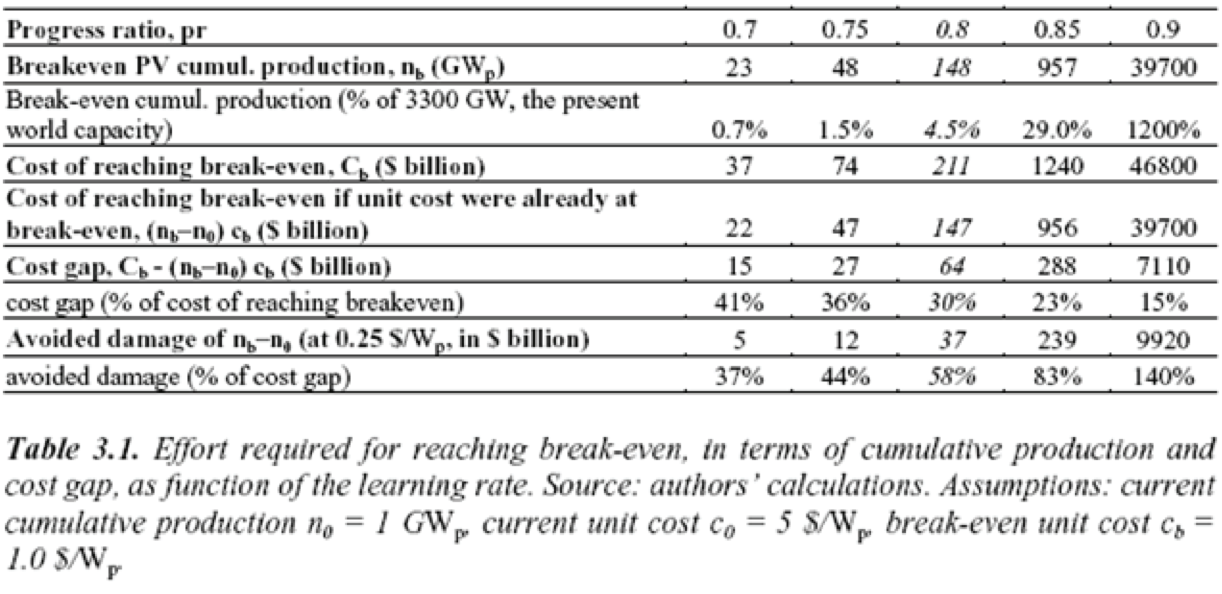
Discussion:
The paper is just a very short update of PV experience curves. Only module price data and module progress ratios are presented. A more detailed scenario for the future learning investments is not given in the article.

2.2.4 [Zwaan et al. 2004]

This study does not only review experience curves, but addresses the potential for PV cost reductions. At first the authors give an overview of current PV production costs which range for example from 2-8 $/Wp for grid connected systems quoting the works of [Turkenburg 2000] and [Oliver; Jackson 2000]. With assumptions for PV systems lifetime (25 years), interest rate (5%), energy earnings (1,5-2,0 kWh/Wp/yr) and O&M costs (2%/yr) price ranges for PV electricity costs from 0,091-0,182 $/kWh for grid connected systems and 0,182-0,303 $/kWh for stand-alone systems are given.

The following part gives an overview of progress ratios of other studies such as [Williams et al. 1993];[Watanabe 1999] and [IEA 2000] whose results are included partly in the overview of PV experience curves in section 2.2.7. The authors calculate that the BEP should be around 1 $/Wp to reach, at least in sunny regions, the currently competitive electricity price of 0,04 $/kWh. Taking the average price for grid-connected systems of 5 $/Wp the necessary cumulative production to reach the BEP is shown for learning rates between 0,7-0,9 (see Figure 2-4). Looking at the numbers the authors emphasize that a progress ratio higher than 0,8 means that the BEP will become elusive. Even with a progress ratio of 0,8 the cumulative production needs to be 148 GW which is 4,5% of the world-wide power plant capacity of the year 2002. The costs of reaching the BEP are calculated by an integration under the experience curve and is about 211 billion $ for the 0,8 progress ratio, which means a learning investment or cost gap of 64 billion $.

The interesting question of including so called “avoided damage costs” from todays energy technologies is also analysed. The authors summarize different sources in the literature and conclude that around 0,01 $/kWh is a realistic value. With the other assumptions mentioned above, this equals a credit for avoided damage costs of 0,25 $/Wp and raises the BEP therefore to 1,25 $/kWh. In the case of the 0,8 progress ratio this means a remarkable decrease of 58% of the learning investments.



Progress ratio, pr	0.7	0.75	*0.8*	0.85	0.9
Breakeven PV cumul. production, n_b (GW_p)	23	48	*148*	957	39700
Break-even cumul. production (% of 3300 GW, the present world capacity)	0.7%	1.5%	*4.5%*	29.0%	1200%
Cost of reaching break-even, C_b ($ billion)	37	74	*211*	1240	46800
Cost of reaching break-even if unit cost were already at break-even, $(n_b-n_0)\ c_b$ ($ billion)	22	47	*147*	956	39700
Cost gap, $C_b - (n_b-n_0)\ c_b$ ($ billion)	15	27	*64*	288	7110
cost gap (% of cost of reaching breakeven)	41%	36%	*30%*	23%	15%
Avoided damage of n_b-n_0 (at 0.25 $/$W_p$, in $ billion)	5	12	*37*	239	9920
avoided damage (% of cost gap)	37%	44%	*58%*	83%	140%

Table 3.1. *Effort required for reaching break-even, in terms of cumulative production and cost gap, as function of the learning rate. Source: authors' calculations. Assumptions: current cumulative production n_0 = 1 GW_p, current unit cost c_0 = 5 $/$W_p$, break-even unit cost c_b = 1.0 $/$W_p$*

Figure 2-4: Table from [Zwaan et al. 2004]

Value of PV:

In this section the paper explains a possible way of how to calculate the value of kWh PV that was needed before in the BEP analysis. Comparing the cost profiles of two typical utility grids in the United States with the energy earnings of PV in this area, values of 0,037-0,038 $/kWh are found. These are significantly higher than the yearly average of 0,28 $ /kWh, because of the higher value of daytime electricity.

Discussion:

The authors give a very good idea of what it means by “riding down the experience curve”. They do not give an estimate of growth rates and time ranges for things to happen, because looking at the costs, the only interesting thing is the progress ratio since this determines at what cumulative capacities the BEP will be reached. Continuing this research it should be examined more intensively, if the BEP should be regarded as constant all over time. There are many reasons like changing energy prices for why the investment cost could be recalculated with different BEP references. In this work therefore a closer look is taken at power exchanges in order to get a more appropriate idea of the value of PV (see Chapter 4).

2.2.5 [Poponi 2003]

Poponi analyses price developments for PV modules between 1976 and 2002 based on price data from Maycock. The performance ratio of his experience curve (75%) is significantly lower than in other studies. This is caused by the big influence of the early years. Starting with the year 1989 the author gets a progress ratio of 80,5% and confirms that this structural break is statistically significant.

In the second part of the work, the module BEPs for two different electricity prices are calculated. With some assumptions (e.g 25 years system lifetime and assuming that modules are responsible for 60% of the system market price) a generating cost of electricity of 0,05 $/kWh (0,15 $/kWh) the BEP for modules is 0,5 $/Wp (1,9 $Wp) and for PV systems 0,9 $/Wp (3,2 $Wp). Finally the different levels of cumulative world PV shipments are estimated which are needed in order to ride down the experience curve to the BEP. In an optimistic scenario of a growth rate of 30% and a progress ratio of 80% the necessary cumulative shipments of 1440 GW (27 GW) could be reached in 2026 (2011) and bring down the PV generating costs to 0,05 $/kWh (0,15 $/kWh).

Discussion:
As Poponi also mentioned the BEPs are highly sensitive to the assumptions that are made: Percentage of module/BOS price with respect to total system price, system lifetime, imputed interest, O&M cost, energy yield, etc.. Including probable changes of these assumptions over the years are not discussed. There are no estimations given about the necessary learning investments to reach the BEPs. This work will evaluate both things, changing break-even prices and necessary learning costs, in the break-even model.

2.2.6 [Schaeffer et al. 2004a]

The final report of the Photex Project is the most comprehensive work on PV experience curves and was published by an international research team, supported by the EU. The main difference between this publication and all other publications so far is the detailed presentation of the used data and the own project database with more than 3600 records, representing 26 MW of primary data. This made it possible not only to construct the typical experience curves for module or system prices, but also experience curves for BOS and inverters. Different countries were also researched separately, although more than 80% of the installed capacity came from Germany, Italy and the Netherlands. To compare the results of their own database, they also bought data for PV module prices from Strategies Unlimited (SU) for the years 1976-2001. In this time frame the progress ratio of the SU data is 80±0,4% while, looking only at 1987-2001, a lower progress ratio of 77±1,5% was obtained which the authors consider consistent with the progress ratio of 74% of the Photex data base for the years 1988-2001. The results for BOS (all components apart from modules) were given for Germany and the Netherlands, because learning should occur in a national context due to differences in building etc., but the progress ratios were nearly the same: 78±1% and 81% respectively. The authors also give progress ratios for an inverter experience curve (based on list prices quoted by manufacturers) for the years 1995-2002 which is 91% in Germany and 93% in the Netherlands. They assume that the higher progress ratio is caused by improvements in efficiency, lifetime and reliability.

Chapter 4 of their publication deals with the question of whether policy programs in different countries can be related to the historical experience curve analysed before. One of the main findings is that countries are difficult to compare because of different national policy strategies and that a large increase in market support temporarily leads to higher module prices, which is of no surprise.

In the following chapter a few price scenarios are first of all given to demonstrate that a growth rate of at least 20% and a learning rate of 20% (= 80% progress ratio) are necessary to obtain low PV prices (see Figure 2-5). Further possible sources of cost reductions before 2010 are examined.

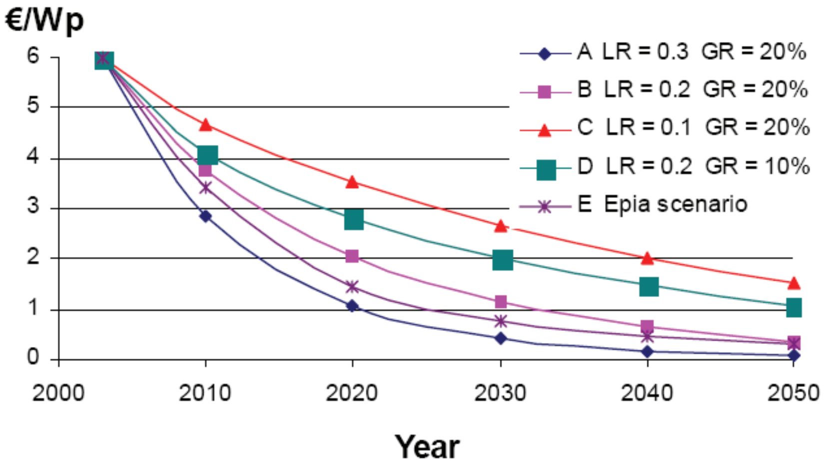


Figure 2-5: Typical price and growth scenarios for PV systems[5]

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[5] Source: [Schaeffer et al. 2004a]

The authors summarize that there are sufficient technical options for modules, inverters and BOS to lower production costs. Prices however will be influenced strongly by an increasing profit range for PV companies, a possible shortage of silicon supply or possible overcapacities in the case of market growth rates of 30% not being maintained.

Chapter 6 deals with a break-even analysis and future learning investments and was strongly influenced by the work of [Zwaan et al. 2004]. At first a scenario for solar-rich regions is given and a BEP of 0,7 €/Wp is assumed (see Table 4-3). A progress ratio of 80% and a growth rate of 20% will reduce PV costs to 0,7 €/Wp in 2039 and the global cumulative learning investments until then will be 634 billion Euro (a decrease of the progress ratio to 75% results in only 193 billion Euro learning investment reaching the BEP in 2031). This shows the high impact of the progress ratio and lets the authors conclude that inversion in improving the progress ratio through R&D support etc. will save society a significant amount of money. Since PV is not likely to compete at first in the bulk electricity market but rather in niche-markets, a different way to calculate the learning investments can be seen in Figure 2-6 following the idea of [Poponi 2003].

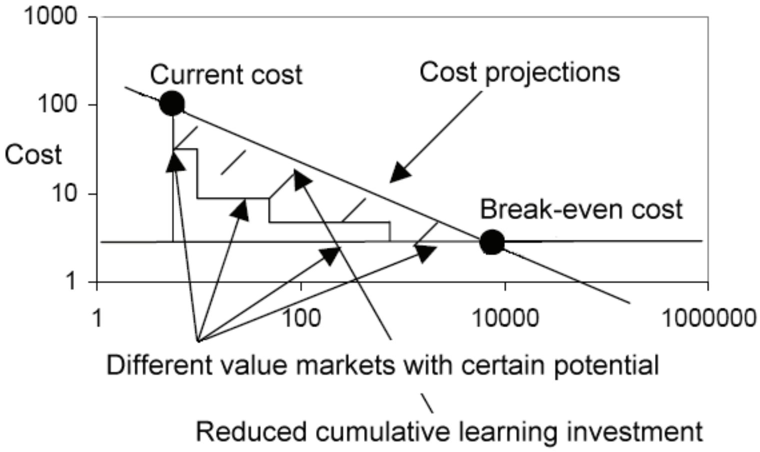

Figure 2-6: Learning investments with niche-markets[6]

Assuming therefore only a BEP of 4 €/Wp results in a cumulative installed capacity of 8 GW in the year 2009 and learning investments of 5 billion Euro, the authors therefore question which balance between learning investments ("total amount of support spent on stimulation of market penetration up to the point of market break-even") or investing in learning ("total amount of support spent on technology development up to the point of market break-even") is adequate.

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[6] Source: [Schaeffer et al. 2004a]

Discussion:
The Photex project made a big effort to collect new primary data for PV experience curves, which should be highly valuated, because it is a very difficult task. One of the main research results done with this primary data is that BOS progress ratios are comparable with module progress ratios: Excluding inverters from the BOS analysis, BOS even has a better progress ratio than modules. Causes for the bad progress ratio for inverters (producers concentrated on efficiency, reliability and lifetime improvements) could be subject to closer examination. Regarding the BEP analysis the Photex project was influenced strongly by the ideas of [Zwaan et al. 2004] and [Poponi 2003] although the results differ reasonably (see Table 2-1). Including niche-markets in the BEP analysis might be a first step to reduce the learning investments on a global level, but more research is necessary (see section 4.5.2 for the results of this work regarding this topic).

2.2.7 Overview of PV Experience Curves in Literature

In the following table the results of the former publications are summarised and the key values are shown. This should give an overview of the research that has been done in the field of PV experience curves up to now. Studies before the year 2000 are not included.

Author	PR (%)	Time Period	Region	Type of EC	Cum. Reference	R^2
IEA (2000)	84%-53%-79%	1976-1996	EU	Modules	ca. 0,8-800 MW	n.a.
Harmon (2000)	79,80%	1968-1998	worldwide	Modules	0,095-950 MW	99%
Parente, Goldemberg, Zilles (2002)	77,20%	1981-2000	worldwide	Modules	ca. 10,5-1500 MW	98,80%
	79,80%	1981-1990	worldwide	Modules	ca. 10,5-250 MW	97,70%
	77,40%	1991-2000	worldwide	Modules	ca. 300-1500 MW	97,80%
Poponi (2003)	75%	1976-2002	worldwide	Modules	4-2380 MW	n.a.
	80,50%	1989-2002	worldwide	Modules	238-2380 MW	n.a.
Photex (2004) SU data	80±0,4%	1976-2001	worldwide	Modules	ca. 0,3-1800 MW	n.a.
	77±1,5%	1987-2001	worldwide	Modules	ca. 100-1800 MW	n.a.
Photex (2004) own data base	74%	1988-2001	EU	Modules	ca. 170-1800 MW	n.a.
Photex (2004) own data base	78±1%	1992-2001	Germany	BOS	ca. 3,9-162 MW	87,80%
	81%	1992-2001	Netherlands	BOS	ca. 0,012-11 MW	93%
Photex (2004) own data base	91±2%	1995-2002	Germany	Inverter	ca. 16-260 MW	84,40%
	93±2%	1995-2002	Netherlands	Inverter	ca. 0,05-8,6 MW	82,80%

Table 2-1: Overview of published PV experience curves

It can be seen that quite a lot of research was done on the development of module prices but little in the field of BOS and so far no study exclusively focuses on type II experience curves, the development of the PV kWh price. This will be one of the principal targets of this thesis (see Chapter 3).

In Table 4-3 of section 4.2.4 the results of break-even price studies and learning investments are summarised. As mentioned before, the learning investments vary widely and are very sensitive to the progress ratio and the break-even prices.

3 PV Experience Curves based on kWh Prices

In this chapter the development of the price of kWh PV is analysed with the use of experience curves. As described above the use of experience curves for kWh prices is not common yet. Therefore the concept of type II experience curves is described in the first section. In the second section the calculation of the PV kWh price is explained and a typical case is presented. In the third section the different factors that influence the PV kWh price are examined and compared with the help of sensitivity analysis. In the following section the way that experience curves are calculated in this work is described and the data for the experience curve construction is presented. With this data the different types of experience curves are constructed and all results can be found in section 3.5. Finally in section 3.6 the interpretations and comparisons of the results take place.

3.1 Concept

Constructing experience curves based on kWh prices is very challenging, because things get more complicated than just using prices for modules. The PV kWh price is influenced by two groups of variables: First, the variables that are responsible for the system price (including cost of installation). These are mainly the prices for modules, inverters, construction materials, planning and installation. The second group of variables are called “soft factors” in this work. They do not directly influence the system price at the time of installation, but they have an important influence on the yearly variable costs or on the yields of a PV system and therefore on the PV kWh price. Among these variables are for example costs of operation and maintenance, system performance ratio, lifetime of the system and degradation of energy earnings etc..

To calculate the price of a kWh-PV the variables of both groups are very important. As mentioned before most of the experience curves just concentrate on cost of PV systems or modules and neglect the improvements of the soft factors that have been made over the years.

3.1.1 From Modules to Systems

When constructing module experience curves it has to be decided whether cost or price data is used. Due to the scarcity of cost data most often price data is preferred. Price data for PV systems can be collected in two different ways: One approach would be a bottom-up analysis that evaluates the price level of each variable of the first group and calculates the total system costs for the PV systems each year. This approach has a big disadvantage: Due to the different sizes of the installations it may not include some important price reductions for bigger installations. It is also questionable, if separated price statistics for modules and inverters are more reliable. The second approach, the top-down analysis, does not look at the different variables separately, but takes into account the complete price of an installation. Surveys and investigations of data from installation owners, PV companies and associations are used to obtain the PV system price of each year. This approach is used in section 3.4.2.2 to get the best overview of the development of the PV system prices. No experience curve can be constructed without reference to the cumulative installed PV systems in this case. Because a PV system is a compound system the question of which references to use becomes important. Sometimes for modules global learning is assumed, while for BOS, local learning seems more adequate. In section 3.4.2.1 the used data for the cumulative reference is described and in section 3.5 the results are presented.

3.1.2 From Systems to kWh Prices

Apart from the system price other soft factors are necessary to calculate the PV kWh price:

- Lifetime of the PV system
- Performance ratio of the PV system
- Degradation of energy earnings
- Yearly variable costs (O&M, insurance etc.)
- Imputed interest

Constructing an experience curve with calculated kWh prices would not give more insight if soft factors were left unchanged over the years. This would just lead to a change of the statistical unit, but without change in the progress ratio or the learning rate. Very interestingly and therefore one of the targets of this thesis is the examination of the PV kWh experience curve with changing soft factors in the course of time. Thus the technical progress that is achieved and not expressed through price reductions of the PV system selling price can be included in the progress ratio of the PV kWh price. But not every factor has the same importance and influences the kWh price in the same manner. For this reason in section 3.3 the sensitivity test of the different soft factors is presented. The data research especially for the soft factors was a difficult task and is described in section 3.4.2. With these results the calculation of the type II PV kWh experience curves can be accessed. For each year the price of a kWh PV is calculated with the different soft factor inputs and related to the cumulative production (see section 3.5.2).

3.2 Price of a kWh PV

To calculate the price of a kWh PV (P_{PV}) the following input variables are used:

C_0 = investment cost of the PV system (turnkey cost) in t=0 in Euro/kWp
n = economic lifetime of the PV system in years
PR_0 = performance ratio, ratio between the nominal performance and the actual performance in the t=0 in%
deg = yearly degradation of energy yields in %
c_v = yearly variable cost factor of C_0 in % (including O&M costs, etc.)
inf = yearly inflation which increases the variable costs in %
k = imputed interest in %
H = yearly total of global irradiation (kWh/m^2/yr) in the plane of the PV modules

The following constant is also necessary:

G = irradiance of STC (1,0 kW/qm at Standard Test Conditions: 25°C and Spectrum of Irradiation AM 1.5)[7]

In the case of PV the annual earnings and costs can be defined as follows:[8]

$\text{Earnings}_t = P_{PV} * H / G * PR_0 * (1\text{-deg})^{t-1}$
$\text{Cost}_t = C_0 * c_v * (1+\text{inf})^{t-1}$

As it can be seen the yearly cash flow of a PV system is only constant if inflation and degradation of energy yields are neglected. Although this would simplify the calculations, in this work the two variables will be used to achieve more realistic results.

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[7] The extraterrestrial solar energy reaching the earth is a constant 1.37 kW/qm and is reduced to 1,0 kW/qm due to the atmosphere etc.

[8] This is only valid, if the degradation of energy yields as well as the inflation start in the second year with a yearly constant percentage of the initial value. The earnings are not corrected by the inflation because the Renewable Energy Law (EEG) provides a constant rate of money for the energy sold, which is not changing over the lifetime of the PV system. For a closer examination of this point see section 3.4.2.7

3.2.1 Theory of Discounted Cash Flow (DCF)

The Discounted Cash Flow (DCF) method can be seen as the central evaluation method for financial investments. The principal idea is to discount the future cash flows of an investment to obtain today's value of the project. In the classical case the following formula is used:

Net Present Value: $NPV = -C_0 + \sum_{t=1}^{n} \frac{Earnings_t - Cost_t}{(1+k)^t}$

If the NPV is positive it shows the advantage of the project compared to an investment with the imputed interest. A negative NPV means that the project will lose money compared to the investment alternative.

The DCF method depends on the assumptions of the future cash flows as well as from the imputed interest k of the fictive investment alternative. The right assumption of k is one of the most difficult tasks when evaluating investment alternatives. In this work the importance of the value of k is shown in section 3.3.7 and the values used are discussed further in section 3.4.2.8. To calculate the price of a kWh PV, the NPV is set to 0 and the formula is transformed like this:

Price of kWh PV: $P_{PV} = \frac{C_0 \times (1 + c_v \times \sum_{t=1}^{n} \frac{(1+inf)^{t-1}}{(1+k)^t})}{H/G * PR_0 \times \sum_{t=1}^{n} \frac{(1-deg)^{t-1}}{(1+k)^t}}$

The result of this equation is the price at which the PV project has the same return of investment like the investment alternative with the imputed interest k.

3.2.2 Annuity Method

In the literature this method is often used [Hoogwijk 2004];[BMU 2004], because the calculation of the price is easier, or at least sometimes easier for presentation reasons, if there are constant earnings and costs over the lifetime of the investment. The investment costs are annualised over the lifetime of the system by multiplying with the annuity factor.

Annuity factor: $a = \frac{k}{1-(1+k)^{-n}}$

The price of a kWh PV can be calculated including the other variables.

Price of a kWh PV: $P_{PV} = \frac{a * C_0 + C_0 * c_v}{H/G * PR_0}$

In this formula neither yearly degradation of the energy yields nor inflation is included, because it assumes constant regular repayments of the invested capital. This certainly could be changed, but would also complicate the formula, so that the advantage of simplicity compared to the DCF-Method would disappear.

3.2.3 Examples: Calculation of a typical PV kWh-Price

The price of a kWh PV depends greatly on the energy earnings or in other words on the irradiation, which the installed system receives. Even looking only at Europe the irradiation can vary widely from 950 kWh/m^2/yr for Finland to 1738 kWh/m^2/yr for Greece [Noord et al. 2004]. For Germany we assume H_{DE} = 1150 kWh/m^2/yr which is also used by other authors [BMU 2004]. To give an impression of how the price changes for Southern Europe we assume a second value H_S of 1700 kWh/m^2/yr which is also used as an average value for calculations on a worldwide basis.[9] For the variables mentioned above values are assumed, which are regarded as typical and common in use for present day technology. A very close examination of these variables is carried out in section 3.4.1. Because of this they are given here without further comment:

C_0 = 5.000 Euro
n = 20 years
PR_0 = 75%
deg = 1%
c_v = 1,5%
inf = 2%
k = 8%
H_{DE} = 1150 kWh/m^2/yr
H_S = 1700 kWh/m^2/yr[10]

The price of kWh PV results in:
$P_{PV,D}$ = 74,0 Cent/kWh
$P_{PV,S}$ = 50,1 Cent/kWh

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[9] For a more detailed analysis of regional irradiances the work of [Dunlop et al. 2005] is also recommended.

[10] Sometimes the capacity factor of an installation is mentioned. It is calculated by relating the energy earnings (862,5 and 1275 kWh/kW$_{peak}$/year) to a theoretical value of 8.760 kWh/yr (365 days, 24 hours full sun). Capacity factor for Germany in our case would be 9,8% and for southern Europe 14,6 %.

The following graph illustrates the dependence on the irradiation:

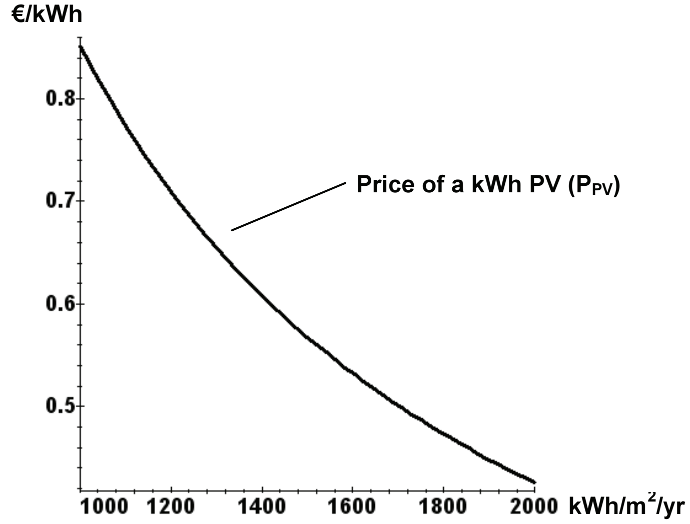

Figure 3-1: Price of kWh PV (P_{PV}) versus irradiation (H)

It can be seen that the example prices of the calculation are quite high. But if comparing this with other publications a closer look has to be given to the assumptions. More often than not, inflation or degradation of energy earnings are neglected and a lower imputed interest is assumed. How these changes of the input variables will influence the price of a kWh PV is discussed in the next section.

3.3 Sensitivity Tests of the different Factors

The change of installation cost of a PV system is normally the main focus when constructing PV experience curves. If you want to construct a PV experience curve on a kWh basis you need to include the changes of the other factors as well. In this chapter we will examine the different variables and their influence on the calculation of a kWh PV. This is done to show the importance of each factor and to demonstrate how an improvement of a factor would lower the price of a kWh PV.

3.3.1 Hard factor: Investment Costs

The initial investment costs C_0 are obviously the most important factor. In the following graph you can see the relationship between installation price and price of a kWh PV for the German irradiation as well as for southern Europe. The relationship is linear. Leaving other factors at their default values a change of the installation cost of 10% leads to a change of the PV kWh price which is also of 10%.

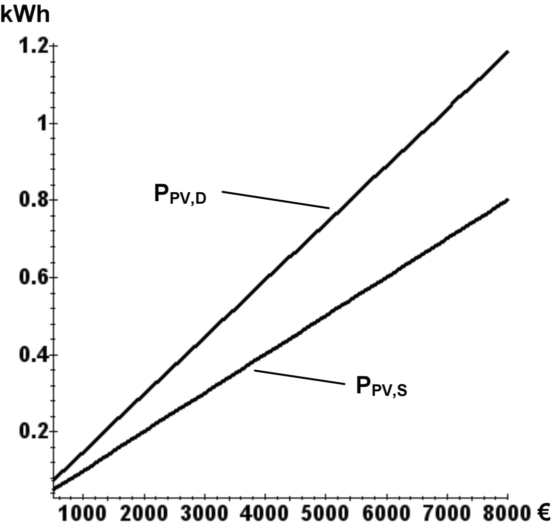

Figure 3-2: Price of kWh PV in Germany ($P_{PV,D}$) and price of kWh PV in Southern Europe ($P_{PV,S}$) versus investment cost (C_0)

3.3.2 Soft factor: Lifetime of the PV System

This factor is called a soft factor, because in experience curves on module or system prices improvements of the system lifetime is not visible.[11] Leaving again all other variables at their default values the PV kWh price depends on the system lifetime like this:

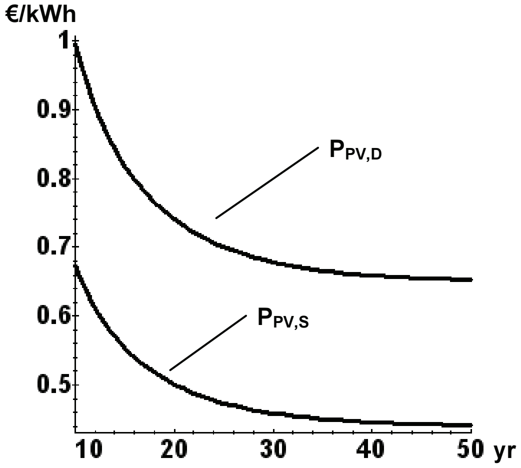

Figure 3-3: Price of kWh PV in Germany ($P_{PV,D}$) and price of kWh PV in Southern Europe ($P_{PV,S}$) versus system lifetime (n)

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[11] PV system lifetime is defined as lifetime of the PV modules in this work. Obviously inverters do not necessarily have the same lifetime as modules, but this fact will be included in the change of variable costs. See section 3.4.2.4

The graph shows that the relationship between PV price and lifetime is not linear. An increase of the lifetime for the German example from 10 to 20 years (100%) results in a PV price reduction of 25,7% ($P_{PV,D,n=10}$ = 99,6 Cent/kWh and $P_{PV,D,n=20}$ = 74,0 Cent/kWh). On the other hand another increase in the lifetime of 100% from 20 to 40 years only reduces the PV price another 10,9% ($P_{PV,D,n=40}$ = 65,9 Cent/kWh). This is caused by the discounting of future cash flows. Depending on the imputed interest the value of the future cash flow is reduced. The sooner the changes of the future cash flow happen the higher is the relevance on the PV kWh price. This effect is more dominant with high imputed interest. Like the sensitivity analysis above showed there is only less than a 12% price decrease possible even extending the system lifetime up to 50 years. The price decrease could be better when the imputed interest and the yearly variable costs are lowered at the same time. In an unrealistic case of no degradation, no variable cost and a zero imputed interest a linear correlation between lifetime and price decrease would exist.

Outlook to the Break-even analysis:
We cannot construct experience curves on a kWh basis and than simply extend this line into the future as is done for experience curves based on the system or module price. This would lead to an erroneous result, because it would imply that an increase of the lifetime always has the same effect. So the prediction of future kWh PV prices will be more difficult. We have to estimate future investment prices with normal experience curves and then research, for each soft factor, the development in the past and its possible changes in the future. These values will then be used to calculate the future kWh PV price (see section 3.5.1.1).

3.3.3 Soft factor: Performance Ratio

The performance ratio PR_0 describes the efficiency of a PV system in the first year. The performance ratio depends, for example, on the efficiency losses of the inverters or cables, but as well as on bad orientated or shadowed installations.[12] If the performance ratio does not stay constant over the years there are decreasing energy earnings, which will be analysed in the next section. The performance ratio in the first year is therefore a good indicator of the quality of a PV system installation. The following graph shows the kWh PV price in relation to the performance ratio:

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[12] Improving the efficiency of a PV module is not part of the performance ratio, because it is included in the investment costs. But an improvement of the temperature coefficient of a module (the decrease of energy earnings due to higher module temperatures) is also a good example of how the performance ratio can change and affect the PV kWh price even if investment costs stay constant.

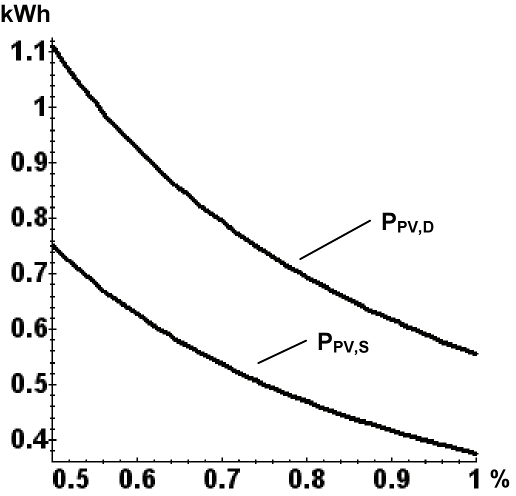

Figure 3-4: Price of kWh PV in Germany ($P_{PV,D}$) and price of kWh PV in Southern Europe ($P_{PV,S}$) versus performance ratio (PR_0)

The improvement of the performance ratio in the past was highly influenced by better planning of the installation, while for the future with present day technology, there exists theoretical limits for the improvement of the performance ratio (see section 3.4.2.5).

3.3.4 Soft factor: Degradation of Energy Earnings

As mentioned before energy earnings do not stay constant over time. The progress ratio of the first year PR_0 is most probably not the same after 20 years of system lifetime, because of degradation of the module output etc.. The relationship between the PV kWh price and the degradation of the energy earnings is shown in the following graph (Figure 3-5). If the degradation could be eliminated a price of $P_{PV,D,deg=0}$ = 69,1 Cent/kWh could be obtained, which is an improvement of 6,6% to the default value. On the other hand, leaving degradation of energy earnings apart and not including them into the calculation of the kWh PV price would lead to erroneous results.

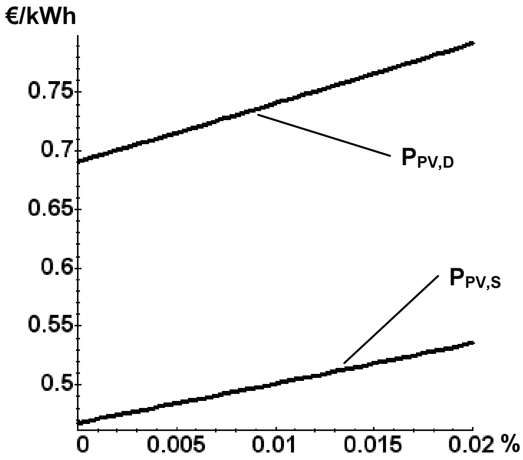

Figure 3-5: Price of kWh PV in Germany ($P_{PV,D}$) and price of kWh PV in Southern Europe ($P_{PV,S}$) versus degradation (deg)

3.3.5 Soft factor: Yearly variable Costs

Although PV has the big advantage that no fuels are needed during operation, a few variable costs such as insurances etc. exist. Also the lifetime of all components of the system may not be the same and in the past inverters for example had to be replaced and therefore increased the variable costs.

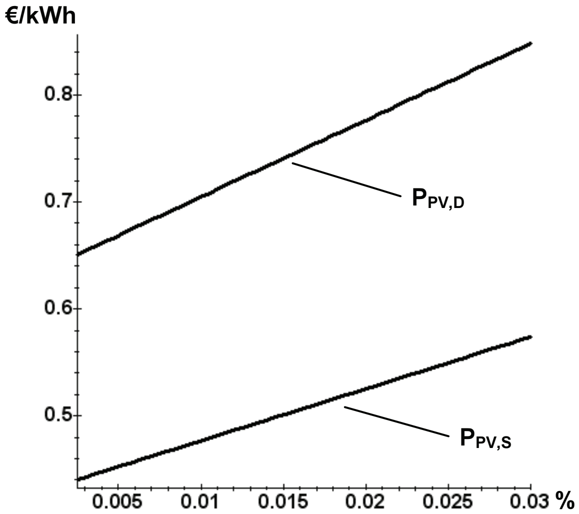

Figure 3-6: Price of kWh PV in Germany ($P_{PV,D}$) and price of kWh PV in Southern Europe ($P_{PV,S}$) versus variable costs (c_v)

In the graph above it can be seen that there is a linear relationship between the PV kWh price and the variable costs. For places with lower irradiation improvements in variable costs have a greater impact. Because variable cost cannot be negative (nor really zero) there is also a visible definitive limit for improvements of this factor.

3.3.6 Soft factor: Inflation

Inflation only influences the PV kWh price on the factor of the yearly variable costs, which increase with time. In some countries the PV kWh price for the energy sold to the public grid is corrected by an inflation factor each year. For these countries no inflation factor in the calculation of the PV kWh price should be used. In Germany this is not the case and the price for selling PV energy to the public grid is fixed on a nominal value.[13] The following graphic shows the influence of the assumed inflation on the PV kWh price:

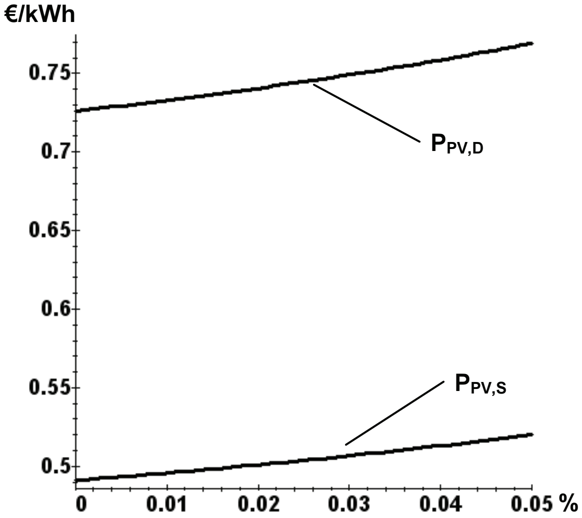

Figure 3-7: Price of kWh PV in Germany ($P_{PV,D}$) and price of kWh PV in Southern Europe ($P_{PV,S}$) versus inflation (inf)

The inflation is not a soft factor that can be changed or improved over time by the solar industry or the owner of PV systems. Although there was variation of the inflation in the past and there will be variations in the future, it makes no sense to include a changing inflation into an experience curve analysis. For our calculations we use a medium value of 2%. This means a small increase of the PV kWh price without inflation from $P_{PV,D,inf=0}$ = 72,6 Cent/kWh to the default value of $P_{PV,D}$ = 74,0 Cent/kWh with inflation.

3.3.7 Soft factor: Imputed Interest

Taking a look at the imputed interest the influence on the PV price is very significant as the following graph shows:

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[13] This implies a certain risk for the investor because of the long duration of his investment. This risk is equal to the risk if buying a normal bond of 20 years duration and is therefore not examined closer here.

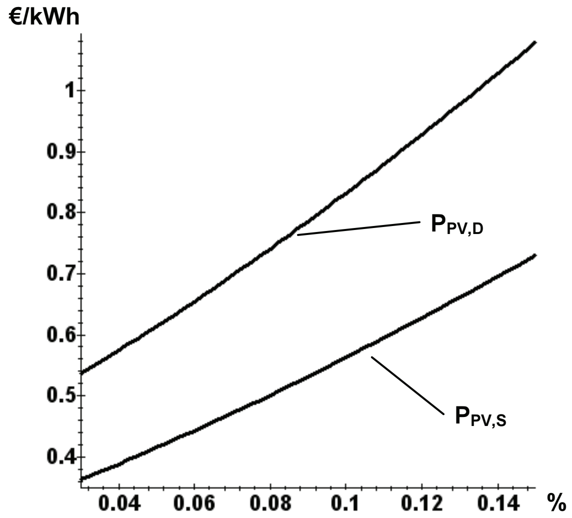

Figure 3-8: Price of kWh PV in Germany ($P_{PV,D}$) and price of kWh PV in Southern Europe ($P_{PV,S}$) versus imputed interest (k)

Comparing the default value of 8% ($P_{PV,D}$ = 74,0 Cent/kWh) with low imputed interest of 3% ($P_{PV,D,k=0,03}$ = 53,6 Cent/kWh) the difference is 20,4 Cent/kWh or 27,6%.

“Which imputed interest should be used to discount the cash flows of an investment” is probably one of the most discussed and most difficult questions of economic science. It always depends on the risk of the planned investment and on the low-risk interest rate that is available on the market. Both things are not constant over time and it has to be discussed whether changes should be included in the experience curve analysis (see section 3.4.2.8).

3.3.8 Results of the Sensitivity Tests for the PV kWh Experience Curves

In the sections above the behaviour of the PV kWh price was demonstrated when changing a certain input variable. This made it possible to see the impact of the variables. For example, improving installation costs always has the same influence on the PV kWh price, while the influence of improving system lifetime decreases greatly when reaching the region of 30 years and more. In the following table, ranges of the PV kWh price are given for every variable and both irradiations: A very optimistic “best value” estimation which might be possible in the future and an “old value” which was used in the early nineties when PV expansion started with the 100.000 roof program in Germany. The default value of each variable is also given in the first column. For Germany the default value calculated before was $P_{PV,D}$ = 74,0 Cent/kWh and for southern Europe $P_{PV,S}$ = 50,1 Cent/kWh.

Variable	Default	Input range	$P_{PV,D}$ in Cent/kWh	$P_{PV,S}$ in Cent/kWh
Investment Cost (C_0)	5.000 €	1.000-8.000 €	14,8-118,5	10,0-80,1
System Lifetime (n)	20 yr	10-50 yr	99,6-65,3	67,3-44,2
Performance Ratio (PR_0)	75%	0,5-1%	111,1-55,5	75,1-37,6
Degradation of Energy Earnings (deg)	1%	0-2%	69,1-79,2	46,7-53,6
Yearly variable Costs (c_v)	1,5%	0,25-3%	65,1-84,3	44,0-57,4
Inflation (inf)	2%	0-5%	72,6-76,9	49,1-52,0
Imputed Interest (k)	8%	3-15%	53,6-107,9	36,3-73,0

Table 3-1: PV kWh price ranges for input variable changes

The main results of the sensitivity analysis, that not all input variables have the same influence on the kWh and that their influence may be different according to the default level, is important for the experience curve analysis. Experience curves on a kWh basis cannot be extrapolated into the future as with normal experience curves, when doing a break-even analysis. Doing this would imply that future improvements of the soft factors will have the same impact on the kWh price as improvements in the past which is not true. Some soft factors have a theoretical limit of improvement like yearly variable cost and degradation of energy earnings, other soft factors such as system lifetime may be extended, but the impact on the PV kWh price will become smaller.

3.4 Construction of PV Experience Curves

In this section the approach to the construction of experience curves is presented in detail. In the first part it is explained according to how the experience curve could be calculated and which approach is preferred in this work. In the second part the data used is described for each of the aforementioned factors. It is important to emphasize that data research in this part was quite difficult in the past and the development of some factors in the future is even harder to predict. For every factor therefore it was intended to find a common estimation of behaviour in literature. This work aims to show a new qualitative approach to analyse the cost decreases of PV and aims not to present an extensive research of every factor. But as well as in the experience curve part as in the break-even part of this work the input variables can be changed easily if new insights of the factor research turn out to be a more appropriate assumption.

3.4.1 Different Ways of Experience Curve Calculation

One big problem of experience research is the difficulty to validate former research results. It is often the case that only graphs and results are given and the exact numbers used for the calculation are missing. It is therefore not possible to redo the calculation or change a few assumptions and reanalyse the result. After personal contact with some of the authors of the above mentioned studies the result was, that experience curve calculation is not done in the same manner all the time. There are mainly 3 different ways to do it: Linear regression with and without weighing and formula resolving. As an example for the regression methods a figure of the Photex final report is shown:

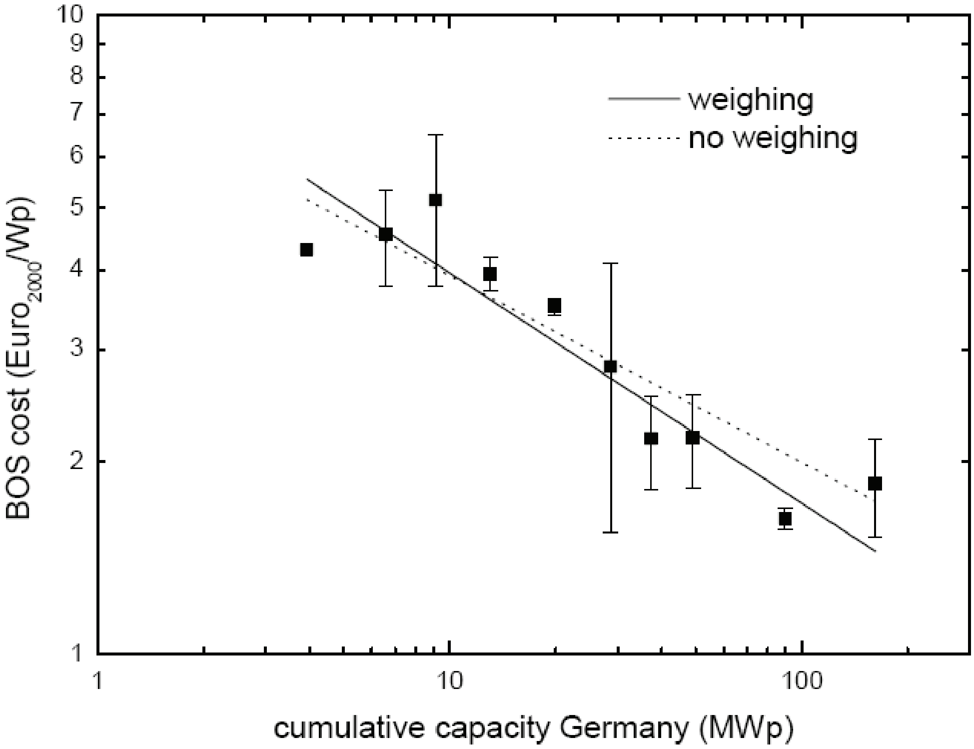

Figure 3-9: Example for Experience Curve Calculation with linear regression[14]

Just resolving the formula with the first and the last value would lead to:

$b = (\log(Cost(x_1)) - \log(Cost(x_2))) / (\log(x_1) - \log(x_2))$

$b = (\log(4,2) - \log(1,8)) / (\log(3) - \log(160)) = -0,213$

PR = 0,863

It is obvious, that this calculation does not include any of the other values apart from the first and the last of the time series and therefore cannot be regarded as trustworthy. Small changes of the start and end value will greatly change the progress ratio. Therefore this method was not used in this work.

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[14] Source: [Schaeffer et al. 2004a]

But even looking at the linear regression methods the difference is not negligible. The progress ratio changes from 81,7% to 77,9% nearly 4% while the R^2 value improves from 0,808 to 0,878. To calculate the linear regression with weighing, information about the uncertainty of the values (standard deviation) is needed. Depending on which values can be trusted more the progress ratio can improve (as in the case above) or worsen.

Because of the different results of the methods it should always be made clear which method was used. In this work the normal linear regression method without weighing is used. The reason for this is that results are easier to compare with those from other studies and data sources can also be used where the uncertainty information is not available, which is mostly the case.

3.4.2 Data Research and Application

In the first section the question of different cumulative capacities is analysed. In the following sections the other input factors are considered. Of particular importance for experience curve analysis is the examination of the learning behaviour of each factor. As global and local (German) growth was quite different in past years it is also discussed whether global or local cumulative capacities should be used as a reference.

3.4.2.1 The Reference: Cumulative Shipment / Installed Capacity

For the results of experience curve analysis the question of the cumulative data used is important. Besides the fact that numbers may differ between different publishers there are a wide variety of references that could be used for the construction of experience curves: Data of produced, sold modules (received from wholesalers or producers), statistics of installed capacity of PV (received from governmental or industry association sources) or statistics of produced MWh PV. Also it has to be considered whether or not local or global references are used for the construction of experience curves. Before starting this discussion an overview of different sources is given:

Region	World	World	World	World	Germany	Germany
Source	Maycock	IEA 2005	IEA 2005	IEA 2005	IEA 2005	BSi/UVS
Type	Cum. Shipments	Cum. Prod.	Cum. Installed	Cum. Grid-connected	Cum. Installed	Cum. Installed
1979	9					
1980	13					
1981	19					
1982	27					
1983	39					
1984	59					
1985	81					
1986	109					
1987	138					
1988	172					
1989	212					
1990	259					1,5
1991	314					2,5
1992	372	230*[15]	110	31	5,6	5,6
1993	432	282	136	42	8,9	8,9
1994	501	336*	164	51	12,4	12,4
1995	579	392	199	66	17,7	17,7
1996	668	467*	245	87	27,8	27,9
1997	793	567	314	127	41,8	41,9
1998	948	693	396	180	53,8	53,9
1999	1150	862	520	276	69,4	69,5
2000	1437	1100	729	452	113,7	113,8
2001	1828	1419	989	670	194,6	194,7
2002	2390	1901	1334	980	278	278
2003	3134	2568	1829	1419	431	470
2004	4329	3728	2596	2144	794	920
2005	6056					

Table 3-2: Cumulative PV shipments / installed capacities in MWp[16]

Comments on the numbers:

Early on Maycock began to publish numbers on PV shipments. Since 1992 the IEA Photovoltaics Power Systems Program (IEA-PVPS) has also published a yearly report about Photovoltaic which contains detailed numbers of 19 countries including installed grid-connected or off-grid systems and numbers of production. The big difference between Maycock shipments and IEA production is hard to explain, because the IEA data differs between production and installation. Obviously Non-IEA

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[15] *Values 1992, 1994, 1996: Cumulative production estimated from the yearly production and cumulative installed numbers;

[16] Sources: [European Commission 2004];[Maycock 2005];[EurObserv'ER 2006];[IEA 2005]: No values for 1991 and earlier; [Schaeffer et al. 2004b];[BSi/UVS 2005]: Values for 2003 and 2004 were corrected at the end of 2005

countries like China and India are becoming more important PV production countries (especially in recent years), but should not account for the difference of over 500 MW as in the year 2003 for example.

Regarding the German numbers it must be said that there are lots of different publications, with slightly different numbers but an analysis of the Photon magazine showed, that they use the same source [Kreutzmann et al. 2005]. The IEA data collection for Germany is done by Christoph Hünnekes and Lothar Wissing in cooperation with the German PV industry association BSi/UVS. That also explains why the IEA numbers are exactly the same apart from the years 2003 and 2004 where BSi/UVS corrected their numbers [BSi/UVS 2005]. This correction was necessary due to a new survey of nearly 900 German electricity companies which was done by Photon magazine [Kreutzmann et al. 2005] and showed dramatically different numbers for the year 2004 (716 MW new installed PV Systems compared to 363 MW of BSi/UVS). These efforts of Photon magazine will be an important step to gain a more reliable data basis of German PV capacities until an obligation of a registration for PV systems may be introduced.

3.4.2.2 PV Module / System Prices

Modules Worldwide:
As mentioned in the section above Maycock began in the early days of PV with annual surveys of the PV industry. Until now it is the most widely used source for PV module price data (e.g. [Zwaan et al. 2004];[Poponi 2003], etc.). In the following table the nominal module prices and the inflation corrected price are given:

Year	Modulprice in $\$_{2001}$	Modulprice in $ nominal
1979	31,71	13
1980	25,79	12
1981	19,48	10
1982	16,52	9
1983	13,78	7,75
1984	11,93	7
1985	10,7	6,5
1986	8,08	5
1987	6,24	4
1988	5,61	3,75
1989	6,07	4,25
1990	6,44	4,75
1991	5,85	4,5
1992	5,36	4,25
1993	5,21	4,25
1994	4,78	4
1995	4,36	3,75
1996	4,51	4
1997	4,58	4,15
1998	4,35	4
1999	3,72	3,5
2000	3,6	3,5
2001	3,5	3,5
2002	2,95	3

Table 3-3: Module prices world from Maycock[17]

Modules in Germany:
Looking at Germany three main data sources were found: Numbers from IEA which come originally from the BMU (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit), numbers from the Photex Project and from the KfW (Kreditanstalt für Wiederaufbau), which monitored the 100.000 roof-top program in the years 1999-2003.

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[17] Source: [Maycock 2005]

Source	**Photex in €$_{2000}$/Wp**	**IEA/BMU in €$_{2000}$/Wp**	**KfW All in €$_{2000}$/Wp**	**KfW <10kW in €$_{2000}$/Wp**	**Own in €$_{2000}$/Wp**
Data volume	**7,0 MW**	**n.a.**	**56,8 MW**	**8,4 MW**	**n.a.**
1992	7,16	6,68			6,92
1993	6,09	6,39			6,24
1994	5,44	5,70			5,57
1995	5,40	5,06			5,23
1996	5,66	4,59			5,13
1997	4,63	4,20			4,41
1998	4,48	3,74			4,11
1999	4,25	3,62	5,00	4,75	4,40
2000	4,45	3,58	4,52	4,50	4,26
2001	5,26	3,48	4,96	4,87	4,64
2002	4,57	2,96	4,26	4,29	4,02
2003		2,4-9,33		3,71	3,71

Table 3-4: Module prices Germany[18]

Comments about the numbers:
IEA/BMU numbers are most often a lot lower than KfW or Photex data. Especially the values from 1999 to 2002, which are very low, this changed in 2003 when a price range was given. The KfW data is of very high quality and the numbers of all installations and commercial installations smaller than 10 kW are very similar. Although the 100.000 roof-top program had 300 MW the KfW was only able to give prices for installations of ca. 57 MW, which is still far more than the data volume of the Photex project. This is surprising, because the Photex Project mentioned in the final report [Schaeffer et al. 2004a], that a big part of their data was also received from the 100.000 roof-top program. In the last column the average of the different sources is given to get an equalised price series.

Systems in Germany:
For PV system prices in the following table the same data sources were used as for German module prices.

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[18] Sources: [Schaeffer et al. 2004a];[IEA 2005];[KfW 2004] and yearly reports from http://www.kfw.de; KfW<10kW are values only from commercial installations without sales tax

Source	Photex in €$_{2000}$/Wp	IEA/BMU in €$_{2000}$/Wp	KfW All in €$_{2000}$/Wp	KfW <10kW in €$_{2000}$/Wp	Own in €$_{2000}$/Wp
Data volume	**7,0 MW**	**n.a.**	**56,8 MW**	**8,4 MW**	**n.a.**
1992	12,78	11,43			12,11
1993	13,32	10,69			12,01
1994	11,15	9,73			10,44
1995	10,14	8,65			9,39
1996	9,05	7,88			8,46
1997	8,66	7,16			7,91
1998	8,23	6,56			7,39
1999	7,32	6,17	7,37	6,87	6,93
2000	7,42	6,54	6,30	6,13	6,60
2001	8,35	6,32	6,54	6,44	6,91
2002	6,42	5,44	5,56	5,62	5,76
2003		4,88		4,83	4,86

Table 3-5: German PV system prices

Comments about the numbers:
As in the modules case the IEA/BMU numbers are lower than the Photex data, but quite similar to the KfW data. The 2001 Photex value of 8,35 seems to be very different compared to the other data sources. In the last column again the average of the data sources is given. With this data it is possible to construct the first PV systems experience curves and study the learning behaviour of PV modules and systems (see section 3.5.1.2).

3.4.2.3 Lifetime of the PV System

Before starting the analysis of the lifetime of the PV system it is important to say that it is the lifetime of the modules which is meant. The lifetime of the inverter can be different and will be discussed in section 3.4.2.4. The lifetime of the modules is one of the most important soft factors as the sensitivity analysis showed. Because modules learn on a global basis [Schaeffer et al. 2004a], the change of the lifetime experiences also has a global learning effect. Therefore a relationship between the global cumulative module production and the improvements of module lifetime was researched.

As literature analysis shows, the examination of the module lifetime is a difficult question. PV modules cannot be tested in a stress test, which is suitable for other products (e.g. chairs, lights or hard disks) and this means that using them in normal conditions means you really would have to wait until the end of their lifetime to know the true module lifetime. For the analysis here the proxy of the producer´s product guarantees is used [Green 2005]. With this data we can assume the lifetime of modules as follows: In the year 1990 around 15 years, in the year 1995 around 20 years and in the year 2003 around 25 years.

Relating these numbers to the global cumulative module production a progress ratio of 1,14 is obtained. This means that with every doubling of the cumulative production the lifetime of the modules could be extended by 14%. It is obvious that this value has a high insecurity, but because of the scarcity of other data it will be used in this work.

3.4.2.4 Yearly variable Costs

As seen in the sensitivity analysis the yearly variable costs can influence the kWh price reasonably, but the improvement possibilities are limited, because there will always be some variable costs. As the calculation of the variable costs is done through a percentage of the installation price, it is important to point out, that with decreasing installation prices nominal decreases of the variable costs are assumed. The change in the percentage of the variable costs would imply therefore that variable costs learn faster than the installation price. But would this be a valid assumption?

On the one hand you certainly have improvements in the inverter lifetime or in the system surveillance which will have positive effects on the variable costs.[19] On the other hand there are variable costs for insurance, land rent, etc. which do not depend on the module price and will play a major role in the future. Therefore it would be too optimistic to assume that the percentage of variable costs could be decreased a lot. It

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[19] The importance of the inverter lifetime for the variable costs tends to be overestimated. A short example should clarify this. The question is: How much would the annual variable costs increase, if lifetime of an inverter is not the same as system lifetime, but only 10 years? To answer the question the yearly savings are calculated which are necessary to buy a new inverter after 10 years.

Assumptions: Growth of the market 30%; Progress ratio 0,8%; Discount rate 6%; Percentage of inverter cost of total installation cost 15% [Haas 2004].

Due to learning effects the replacement price in 10 years would only be 6,4% of the present day total installation cost. To reach this amount of money in the tenth year, every year savings of 0,49% must be achieved.

A prolongation of the inverter lifetime from 10 years to the same lifetime as the modules (which would be very ambitious) could only save 0,5% of variable costs. This effect will probably be compensated by increasing cost for land rent, which did not occur as much in early times of PV installations.

is even questionable whether the percentage of 1,5% can be maintained over a long time period, if module prices decrease quickly. Therefore in this work the variable costs are assumed as a constant factor of 1,5% of the installation costs as long as the experts do not come to another substantiated opinion.

3.4.2.5 Performance Ratio

The performance ratio has a big impact on the PV kWh price as can be seen in the formula in section 3.2.3, because it defines which percentage of the irradiation can be transferred in electric energy. Experience curves that are only based on installation prices cannot include the change of this important factor. In literature several studies can be found of PV performance ratios whose main results are summarised in the following table:

Study	Scope	Main Results
[IEA 2002]	Countries: Japan Years: 2000 Number of systems: 85	Average annual yield: 990 kWh/kWp Average PR = 0,74 “A large dispersion is found in the final yield and performance ratio.”
[Jahn et al. 2000]	Countries: worldwide Years: 1993-1997 Number of systems: 170	Average annual yield: 700 kWh/kWp Average PR = 0,66 “A tendency of increasing annual PR values during the past years has been observed.”
[Jahn and Nasse 2004] and [Jahn et al. 2004]	Countries: Germany, Austria, Italy, Netherlands, Switzerland Years: 2000 Number of systems: 235 Germany 22 Austria 29 Italy 20 Netherlands 62 Switzerland and others	Germany: Average annual yield: 730 kWh/kWp 1991-1994: Average PR = 0,65 1996-2002: Average PR = 0,74 “Comparing early PV installations (1991-1994) and new installations (after 1996) in Germany, a significant rise in mean annual PR of 13% was found.” Europa: Before 1995: Average PR = 0,65 After 1995: Average PR = 0,70 ”This is a significant rise in PV system performance and reliability gained in these 11 countries during the past eight years of installation.” “Despite good results, which have been obtained by many of the new grid-connected systems, the investigation of the operational behavior of the reported PV systems has identified further potential for optimisation. Average annual PR values of higher 0.75 are to be achieved for well-planned PV systems.”
[Decker et al. 1995]	Countries: Germany Years: 1993-1994 Number of systems: 172	Average PR = 0,665 “Using the annual in-plane irradiation we determine annual performance ratios in Average annual yield: 680 kWh/kWp”
[Huld et al. 2005]	Theoretic study about the relative efficiency of crystalline Si modules.	“The theoretical performance ratio limits due to temperature effects in the European continent are in the range 0.88 (Southern Spain) to 0.95 (Northern Scotland).”

Table 3-6: Literature overview of performance ratio studies

In analysing the results of the studies, a clear tendency of increasing performance ratios over the last years has been observed. Also with normal crystalline modules there is still a long way to go to achieve the theoretically possible high performance ratios of between 0,88 and 0,95 [Huld et al. 2005]. As the performance ratio is just a definition value, higher ratios of more than 1 could be achieved with other technologies, but this possibility is not assumed in this work. The performance ratio experiences mainly local learning effects: Better inverter performance, improvements in planning (pure installation quality, decreasing shading, module mismatch), higher system availabilities through better maintenance, etc.. Therefore the improvements in the performance ratio are related to the local cumulative capacities. With our assumption of performance ratios of 65% in 1990, 70% in 1995 and 75% in 2003 a learning curve with the progress ratio of 1,017 is obtained. With every cumulative doubling in the installation an improvement of nearly 2% in the performance ratio could be seen.[20] Improving the performance ratio remarkably in the future (e.g. through different cell technologies or high module temperature behaviour) might make an adaptation of the progress ratio necessary.

3.4.2.6 Degradation of Energy Earnings

While in the section before the focus was on the performance ratio which can be obtained in the first year of the installation and which depends mainly on the local installation experience, in this section the degradation of energy earnings is discussed: namely that which is caused by the modules over the lifetime of the PV system. This is also called long-term degradation in contrast to short-term degradation which happens in the first hours of module exposure to the sun and is normally compensated by the producer of the modules through lower nominal power declaration. A change in module degradation would obviously be related to the global capacities (equally to module experience curves). Literature research has shown, that degradation issues are difficult to prove. Firstly, because of the long-term horizon of the tests, there are few institutions (e.g. the TISO institute) that assess the topic. Second, degradation happens in very small units, so that level of uncertainty makes it difficult to get reliable results.

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[20] [Heilscher et al. 2006] reports in his publication a strong increase in the kWh/kWp energy earnings for the years 2001 to 2004, which would imply a faster learning than in other studies. But in the paper progress ratios are not calculated and it is not visible if these effects also occur due to the faster growth of PV systems in the South of Germany compared to the North.

Vaaßen´s shows that most of the studies of module degradation reach from 0-1% with the majority under 0,5% [Vaaßen et al. 2004]. Paretta examined a 600kW PV plant in Italy in the years 1986 and 1992 and found a yearly degradation between 1-1,5% for the modules installed in 1986 [Parretta et al. 2001]. While Kiefer could not find a tendency to module degradation in the examination of the first 10 years of the PV system of the German 1.000 roof-top program [Kiefer et al. 2003]. Dunlop on the other hand finds yearly degradation of 0,1-0,7% [Dunlop 2003] which corresponds very well to the finding of 0,2-0,7% of the TISO institute [LEEE-TISO 2004].

Analysing the literature it can be said, that in the early years of PV modules degradation was higher, while most recent studies show less degradation of crystalline Si modules. For the new thin film technologies there is no reliable data available at all.

In this work therefore the following yearly module degradation in the year of installation is assumed: 1985 1,5%, 1990 1%, 1995 0,75% and 2003 0,5%. Relating this to the global module capacities, a progress ratio of 0,81 is obtained.

3.4.2.7 Inflation

Inflation matters in different ways in the experience curve analysis: First the nominal prices of past years must be corrected by a deflation factor to include the inflation in the experience curve calculation. In the following table the numbers of this factor with the corresponding yearly changes are given for Germany and also for the worldwide prices.

Year	Germany		Worldwide	
	Deflator 2000	Inflation	Deflator 2001	Inflation
1984	0,726	2,0%	0,587	4,3%
1985	0,742	2,2%	0,608	3,5%
1986	0,766	3,2%	0,619	1,9%
1987	0,780	1,8%	0,642	3,7%
1988	0,791	1,5%	0,669	4,2%
1989	0,810	2,4%	0,700	4,7%
1990	0,836	3,2%	0,738	5,4%
1991	0,852	1,9%	0,770	4,3%
1992	0,895	5,0%	0,793	3,0%
1993	0,928	3,7%	0,816	3,0%
1994	0,951	2,5%	0,837	2,5%
1995	0,970	2,0%	0,861	2,8%
1996	0,980	1,0%	0,887	3,0%
1997	0,987	0,7%	0,907	2,3%
1998	0,998	1,1%	0,921	1,6%
1999	1,003	0,5%	0,941	2,2%
2000	1,000	-0,3%	0,972	3,3%
2001	1,013	1,3%	1,000	2,8%
2002	1,029	1,5%	1,017	1,7%
2003	1,040	1,1%		
2004	1,048	0,8%		
2005	1,054	0,5%		

Table 3-7: Inflation Germany and World[21]

Secondly inflation can influence the kWh price calculation. In the sensitivity analysis, it was mentioned before, that inflation must not be included in the calculation if the feed-in tariff is corrected by a correction factor (for example in Spain). If this is not the case or if the system does not get any feed-in tariff, inflation is included in the calculation of the kWh price. In this work the German average of inflation over the last 20 years of 2% is used as a constant input for the kWh price calculation. Inflation changes are not dependent on experience curve effects of solar energy and therefore inflation must be assumed as constant in experience curve calculation of the past and future break-even analysis.

3.4.2.8 Imputed Interest

As we saw in section 3.3.7 the price of a kWh PV is very sensitive to the imputed interest used. When comparing studies where PV kWh prices are calculated it is very important to know which imputed interest was applied. The variety of imputed interests is large and reaches from 3% to over 10% (e.g. [BMU 2004];

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[21] Sources: http://www.bundesbank.de; [Poponi 2003]

[Dunlop et al. 2005];[Hoogwijk 2004];[Poponi 2003]). But apart from Poponi, who discusses the aspect of finding an appropriate imputed interest, all other studies just assume one without giving reasons for that assumption.

How to find the right imputed interest:
In finance theory the imputed interest expresses the anticipated risk of the future cash flows of an investment. Every risk of an investment can be separated in two parts: The general market risk, which interest rate is the one of an alternative low-risk financial investment of long term state government bonds, and the specific project risk of the planned investment. To incorporate the specific risk of an investment the imputed interest is usually defined like this:

$k = i+r$
i = low-risk interest rate
r = interest rate for specific risk of the investment (risk corrected capital costs)

Both parts are changing over time for different reasons:
Interest rate i is changing, for macroeconomic reasons. These changes are not predictable and past values are just an indication for future developments. Therefore in finance theory the duration of the long term state government bonds is used. For Germany for the last 20 years from 1986 until 2005 the duration was 6%[22]. Although theoretically i is changing over time for the experience curve and break-even analysis it must be fixed on a certain level and assumed as a constant part of k.

Interest rate r is changing, because the risk of a PV project is not constant overtime. It depends on the diffusion of solar energy and the knowledge of the sector, in other words, the learning. Therefore it is obvious, that with the spread of solar technology the specific risk of an investment in this technology decreases. This can be seen clearly in the conditions of bank loans for PV projects. While in the early nineties, it was nearly impossible to get a loan for a PV system, nowadays you get special interest rates and the system itself is accepted as bank security[23]. Hence, early investors had to calculate with a higher specific risk, meaning higher risk corrected capital costs r. In other words it can be said, that the part r of k has experienced learning over time which must be included in the PV price calculation for the different years and thus in the experience curve calculation. Because the loans for PV

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[22] exactly 5,93% calculated on monthly bases from [Bundesbank 2006]. Since 2004 there are historically low interest rates of around 4%, but it would be too optimistic to assume this level for a long term model.

[23] for example: http://www.umweltbank.de

systems differ from country to country this factor should be related to the local capacities.

It is difficult to estimate the value of r for the early nineties, because the market was so small and totally dependent on subventions. For high risk investments in economic science imputed interests of 15% or higher are used (r=9%), which also seems adequate in our case. For the later years the solar fonds can be used as an indicator. An overview of actual fonds of 2005 offer a interest rate of 5-8% [Siemer 2005]. Because the low-risk interest rate for the year 2004 was 4% [Bundesbank 2006], the value for r was between 1-4%. For the year 2003 therefore r=3% is very reasonable and is used in this work.

Relating these numbers of r to the local cumulative capacities a progress ratio of 0,87 is obtained. This is the progress ratio of r and to this must always be added the low risk interest rate i to obtain the imputed interest k (for the year 2003 k=9% for example). Under some circumstance one could argue, that r could also be negative in the future. An example for this scenario is, the perception of investors that investing in solar energy will diversify their portfolio and risk. Due to a negative correlation with other investments like stocks or bonds a negative r might be accepted. This would mean that investing in PV lowers the risk under the low-risk interest rate that is available at the market and therefore a lower imputed interest is accepted by the investor. It is very questionable if this will ever happen and therefore is not included in the scenarios in this work.

3.5 PV Experience Curves

After the data research in the last section it is now possible to calculate PV experience curves not only on the basis of module or system prices, but also on the basis of kWh prices. In this section the results of different experience curve calculations are presented. The first section deals with type I experience curves and the second section with type II experience curves, comparing the results. Most experience curves are constructed for the years 1992 to 2003, because the most reliable data was available for that time. But in section 3.6.2 an update can be found until the year 2005.

3.5.1 Type I Experience Curves

Starting with type I experience curves the problem of different cumulative capacities is analysed. After this experience curves for modules and for German system prices are presented and the results are interpreted.

3.5.1.1 Experience Curves with different cumulative References

In this section the progress ratios (PR) for different cumulative references were calculated for the years 1992 to 2002. This time frame was chosen, because the most reliable price data was available for this period (for the newest developments see section 3.6.2). As price reference 3 different prices were used: Worldwide module prices from Maycock, German module prices from IEA and German PV system prices from IEA. The results are given in the following table.

Year 1992-2002, Different Cumulative Capacities		**Price Module World Maycock**		**Price Module Germany IEA**		**Price System Germany IEA**	
	Cum.Doubl.	**PR**	**R^2**	**PR**	**R^2**	**PR**	**R^2**
Module World Maycock	2,7	81,65%	0,938	74,29%	0,929	76,77%	0,890
Module World IEA produced	3,0	83,57%	0,934	76,76%	0,937	79,00%	0,901
Module World IEA installed	3,6	86,26%	0,930	80,45%	0,929	82,41%	0,891
Module World IEA grid-connected	5,0					87,27%	0,880
Module Germany IEA installed	5,6			86,59%	0,955	87,92%	0,925

Table 3-8: Experience curves of modules and PV systems 1992-2002 with different references

References for module prices worldwide:
Looking at Maycock´s PR for module prices worldwide, the results for the cumulative capacities of Maycock and IEA produced are very similar, less than 2% difference. Although the absolute numbers of IEA produced capacities are very much below Maycock´s numbers, the cumulative doublings are almost identical: 3 and 2,7 times respectively from 1992-2002. The PR for IEA installed would be worse, but can´t be regarded as a valid result, because the learning of the modules affects all modules produced and not only the installed ones in the IEA countries. Thus for worldwide module price reference, the Maycock cumulative capacities will be used throughout.

References for module prices in Germany:
The importance of choosing the right cumulative reference can be clearly seen in the case of German module price. In relation to the global module shipment of Maycock data the PR is 74,3%, while in relation to the German market the PR rises to 86,6%, which is nearly half the learning rate. Looking at the cumulative capacity doublings of 5,7 times for Germany compared to only 2,7 for the world market, the reason is obvious. The German market at that time period grew a lot faster than the global market. As mentioned also in the Photex Project modules learn in a global learning system and are produced and traded on a global market world wide

([Schaeffer et al. 2004a]). It would therefore be wrong to relate them to a local learning system using German cumulative capacities.

References for German PV system prices:
Cases such as these are more difficult, because a PV system is a compound learning system. If growth within the German market is quite different from the global growth (which was particularly true from 2000-2004) the results can differ a lot. In this case i.e. between the local and the global reference, a PR difference of approximately 11% exists.
Reasons for using global capacities:

- The largest proportion of costs refer to the modules.
- A mayor part of the BOS cost belongs to inverters. These are also becoming more globalised products.
- Databases for local cumulative capacities are more insecure.

On the other hand there are reasons that favour using local capacities:

- Some portions of the BOS learning experience depend on the number of locally installed systems, rather than on modules that have already been produced.

As the error of relating PV system prices to global cumulative capacities is a lot smaller than relating them to local cumulative capacities, in this work PV system prices are related to global capacities. The problem of which reference to use (global or local) only arises if growth rates of both markets are extremely different. It can be seen with other industries that with ongoing time the growth rates of the fast movers (Germany, Japan, United States in the case of PV) will converge with the global growth rates. This hopefully will lead to smaller differences and challenges of the reference question.

3.5.1.2 Experience Curves of Modules

In this section the different experience curves for German PV module prices are compared. As were shown in the section above the experience curve for modules should always be calculated using global cumulative shipments as reference (Mayock, Cum. Doubl. 2,7):

Year 1992-2002, German Module Prices	PR	LR	R^2
Price Module D Photex	87,50%	12,50%	0,53
Price Module D IEA	74,29%	25,71%	0,92
Price Module D Own	84,08%	15,92%	0,73

Table 3-9: Experience curves of different German module prices 1992-2002

The calculated PR of 87,5% of the Photex data of the years 1992-2002 seems very high compared with the value of 74% which is mentioned in the Photex report for the years 1988-2001 (although the module prices of all countries were used, not only the ones of Germany as in this work) [Schaeffer et al. 2004a]. Also the R^2 value is extremely dissatisfactory. The difference may originate from very high prices during the first four years of the other countries, not Germany. For the IEA data a lower PR is achieved and the R^2 is also a lot better. The own data set is in between the others, but still with a poor R^2 value. For comparison only and because of the high quality of the KfW price data (installations < 10 kW) the progress ratio of this data set also is calculated. Due to the short time period during the years 1999-2003, the cumulative doublings of the world market in these years were only 1,4 times. The calculations return a PR of 84,1%.

3.5.1.3 Experience Curves of German PV Systems

As mentioned in section 3.5.1.1 for PV systems the reference question has to be discussed, when global and local growth are very different. In the following table therefore the experience curves are calculated against the global cumulative capacities of Maycock and the German cumulative capacities of IEA.

Years	German System Prices	Module World Maycock			Module D IEA		
		Cum. Doubl.	PR	R^2	Cum.Doubl.	PR	R^2
1992-2002	Price System D Photex	2,7	78,30%	0,84	5,6	88,82%	0,86
1992-2002	Price System D IEA	2,7	76,77%	0,89	5,6	87,92%	0,92
1992-2002	Price System D Own	2,7	76,20%	0,92	5,6	87,65%	0,94
1999-2003	Price Module D KfW <10kW	1,4	80,20%	0,86	2,6	88,92%	0,80

Table 3-10: Experience curves for German PV system prices 1992-2002

Looking at the numbers a range of the progress ratio of 9%-11% is found between global and local cumulative capacities. Interesting however is, that with PV system prices the own price series returns a lower progress ratio and a better R^2 value than both other series' (IEA and Photex). This comes from the effect that in the early years higher prices dominate the average building while in the later years with the influence of the KfW data lower prices were more dominant.

3.5.1.4 Interpretations

Comparisons between module and PV system values (worldwide cumulative capacities): The IEA data has the smallest difference in progress ratio for German module prices (PR=74,3%) and German system prices (PR=76,8%). For Photex data and the own data the progress ratio of PV system is about 8% better than for modules. The effect that all system progress ratios are better than the module progress ratios could be caused by non-module learning effects. The learning of the other parts of the PV system installation price (including planning etc.) was very high in the analysed years. Plotted against the slower growing global PV market this results in high learning rates or low progress ratios. To give an upper limit of the progress ratios they were also calculated against the local German capacities. It is obvious that a value of around 88% is much too pessimistic, because the module learning is calculated against the fast growing local market, but nevertheless it can be seen as a theoretical very upper limit for the progress ratio. For the analysis in this work, especially the relative improvement from the progress ratios of PV system prices to progress ratios of PV kWh prices is of significant interest and is therefore calculated in section 3.5.2.

Resuming analysis of type I experience curves it can be said that a progress ratio for PV systems of 0,8 is justified for the use in the break-even analysis.

3.5.2 Type II Experience Curves

In section 3.4.2 the different soft factors that influence the kWh price have been discussed and their past development has been analysed. In the following table the results of this analysis are shown:

Soft factor	**Learning**	**Progress Ratio**	**Constant Value**
Lifetime of the PV system	Global	1,144	
Degradation of energy earnings	Global	0,812	
Performance ratio	Local	1,017	
Interest rate r Interest rate i	Local No learning	0,876	 6%
Yearly variable cost	No learning		1,5%
Inflation	No learning		2%

Table 3-11: Overview over soft factor results

It can be seen that two factors have been learning globally and two factors locally. In section 3.5.1.1 the problem of global and local references with different growth rates has been discussed. In the following sections the global and the local learning part of the PV kWh price are examined separately.

3.5.2.1 Including Global Learning of Soft Factors

In the type I experience curves made so far, no change of a soft factor was included. In this section the change of the lifetime and module degradation is examined. To do this without influence of the other variables, past theoretical PV kWh prices are calculated. It is assumed that all other variables apart from the lifetime and degradation stay constant to show how the change of these two variables affect the kWh price. For each year therefore the price of a kWh PV is calculated using the formula given in section 3.2.1.

The following constant values are used:
C_0 = 5.000 Euro
PR_0 = 75%
c_v = 1,5%
inf = 2%
k = 9%
H_{DE} = 1150 kWh/qm/yr
H_S = 1700 kWh/qm/yr

In the following table the values for the cumulative capacities worldwide, the lifetime, the degradation of energy earnings and the calculated prices for Germany and Southern Europe are given.

Year	Cum.Cap.World in MW	Lifetime n in yr	Degradation	Price D in €-Cent/kWh	Price South in €-Cent/kWh
1990	259	15,8	1,02%	86,22	58,33
1991	314	16,4	0,96%	83,95	56,79
1992	372	17,0	0,91%	83,73	56,64
1993	432	17,5	0,87%	81,81	55,34
1994	501	18,0	0,83%	81,63	55,22
1995	579	18,5	0,80%	79,96	54,09
1996	668	19,0	0,77%	78,5	53,1
1997	793	19,7	0,73%	78,3	52,97
1998	948	20,3	0,69%	76,97	52,07
1999	1150	21,1	0,65%	75,77	51,26
2000	1437	22,0	0,61%	74,67	50,51
2001	1828	23,1	0,57%	73,66	49,83
2002	2390	24,3	0,52%	72,73	49,2
2003	3134	25,6	0,48%	71,89	48,63

Table 3-12: Theoretical kWh price with values for global soft factor learning

It is important to remember that these kWh price are theoretical because even the installation costs were left constant over time. The experience curve analysis gave the following results:

Years 1992-2002: Progress ratio 0,949
Years 1990-2003: Progress ratio 0,95

The progress ratio is absolutely identical for German and Southern Europe price because the absolute value of the irradiation does not influence the inclination of the experience curve. Neither the installation price nor the performance ratio, when left constant, changed the value of the progress ratio. This is different for the other soft factors. Regarding changes in inflation and variable costs even substantial changes have little influence on the progress ratio calculated above. The situation changes for the imputed interest. This can be seen in the following table for the years 1990-2003.

Imputed Interest	Progress Ratio
6%	0,936
7%	0,941
8%	0,946
9%	0,950
10%	0,954
11%	0,958
12%	0,962
13%	0,965
14%	0,968
15%	0,970

Table 3-13: Theoretical progress ratios including global soft factor learning for different imputed interests

If the imputed interest is lower, the improvements of soft factors like lifetime and degradation have a major effect on the progress ratio.

Interpretations:
The result of a progress ratio of around 0,95 for the combined lifetime and degradation learning is an important finding. This means, that with every cumulative doubling of module production, the price of a kWh PV decreased 5% due to both soft factors (even assuming that all other variables remained unchanged, including the installation price). This price decrease was due to effects of lifetime extension and decrease of degradation. These price decreases of PV are not visible if just type I experience curves of module prices are examined.

3.5.2.2 Including Local Learning

As in the previous section, the influence of the change in the performance ratio and the imputed interest are examined. Again all other variables remain constant with the following values:
C_0 = 5.000 Euro
n = 20 years
deg = 1%
c_v = 1,5%
inf = 2%
H_{DE} = 1150 kWh/qm/yr
H_S = 1700 kWh/qm/yr
The development of the performance ratio and the imputed interest in relation to the local cumulative capacities can be found in the following table as well as the calculated theoretical PV kWh prices.

Year	Cum. Cap. Germany in MW	PR_0	Imputed Interest k	Price D in €-Cent/kWh	Price South in €-Cent/kWh
1990	1,5	65,3%	15,00%	123,88	83,8
1991	2,5	66,1%	14,16%	117,47	79,46
1992	5,6	67,5%	13,00%	108,62	73,48
1993	8,9	68,2%	12,40%	104,16	70,46
1994	12,4	68,8%	12,01%	101,2	68,46
1995	17,7	69,4%	11,61%	98,23	66,45
1996	27,9	70,2%	11,15%	94,71	64,07
1997	41,9	70,9%	10,76%	91,81	62,11
1998	53,9	71,4%	10,54%	90,13	60,97
1999	69,5	71,8%	10,32%	88,5	59,86
2000	113,8	72,7%	9,93%	85,54	57,86
2001	194,7	73,7%	9,55%	82,59	55,87
2002	278	74,3%	9,32%	80,77	54,64
2003	470	75,3%	9,00%	78,28	52,96

Table 3-14: Theoretical kWh price with values for local soft factor learning

The experience curve analysis returned the following results:

Years 1992-2002: Progress ratio 0,949
Years 1990-2003: Progress ratio 0,947

Again for both price series' the progress ratio is identical. However this time the absolute values of the constant soft factors have less influence. Like above for inflation and variable costs even significant changes in the absolute value have little impact on the progress ratio (for example changes of the progress ratio are smaller than 0,005 for doubling of inflation or variable costs). Also assuming lifetime between 15-30 years or a degradation of 2% does not influence the progress ratio by more than 0,005 points.

Interpretations:
Analysis of the local soft factors change shows that there was a remarkable improvement in the performance ratio and the imputed interest due to the increased spread of PV technology and knowledge in Germany. This led to a price decrease of the kWh price of 5% for each cumulative doubling in the previous years in Germany which is not included in the normal type I experience curve analysis. Regarding the change of the imputed interest some may argue that these changes happen with every advancement in energy technology. This certainly is true, but it is not an argument for not including them in the experience curve analysis. On the contrary the

change in the imputed interest should also be included as well in experience curves of other energy technologies.[24]

3.5.2.3 PV kWh Experience Curve for Germany

After comparing global and local learning separately with theoretical PV kWh prices (i.e. without using real changing prices for the PV system) in this section the real price data of PV systems in Germany (from section 3.4.2.2) will be included in the calculation. This continues the analysis of section 3.5.1.3, which has analysed the PV system price without soft factor influence. As in the sections above, first the global and the local learning soft factors are examined separately and in every case, the own price data for PV system is used. The following data shows input constants and variables for the change of kWh prices for PV systems including global soft factor change:

PR_0 = 75%
c_v = 1,5%
inf = 2%
k = 9%
H_{DE} = 1150 kWh/qm/yr

Year	Cum.Cap.World in MW	Price System D Own in €$_{2000}$/Wp	Lifetime n in yr	Degradation	Price D in €-Cent$_{2000}$/kWh
1992	372	12,11	17,0	0,91%	202,73
1993	432	12,01	17,5	0,87%	196,47
1994	501	10,44	18,0	0,83%	170,42
1995	579	9,39	18,5	0,80%	150,23
1996	668	8,46	19,0	0,77%	132,87
1997	793	7,91	19,7	0,73%	123,84
1998	948	7,39	20,3	0,69%	113,81
1999	1150	6,93	21,1	0,65%	105,07
2000	1437	6,60	22,0	0,61%	98,54
2001	1828	6,91	23,1	0,57%	101,8
2002	2390	5,76	24,3	0,52%	83,79
2003	3134	4,86	25,6	0,48%	69,82

Table 3-15: German PV kWh prices with global soft factor change 1992-2003

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[24] Most other energy technologies have higher imputed interests because future cash flows are a lot more insecure. This is obvious because future development of fossil resources is not known or even wind availability is less secure than the solar irradiation.

The experience curve analysis returned the following results:

Years 1992-2002: Progress ratio = 72,32% (R^2 = 0,93)
Years 1992-2003: Progress ratio = 72,25% (R^2 = 0,95)

In the following table, the changes of the local learning soft factors are included:

n = 20 years
deg = 1%
c_v = 1,5%
inf = 2%
H_{DE} = 1150 kWh/qm/yr

Year	Cum.Cap.Germany in MW	Price System D Own in €$_{2000}$/Wp	PR$_0$	Imputed Interest k	Price D in €-Cent$_{2000}$/kWh
1992	5,6	12,11	67,5%	13,00%	263
1993	8,9	12,01	68,2%	12,40%	250,12
1994	12,4	10,44	68,8%	12,01%	211,28
1995	17,7	9,39	69,4%	11,61%	184,55
1996	27,9	8,46	70,2%	11,15%	160,32
1997	41,9	7,91	70,9%	10,76%	145,21
1998	53,9	7,39	71,4%	10,54%	133,26
1999	69,5	6,93	71,8%	10,32%	122,71
2000	113,8	6,60	72,7%	9,93%	112,89
2001	194,7	6,91	73,7%	9,55%	114,14
2002	278	5,76	74,3%	9,32%	93,06
2003	470	4,86	75,3%	9,00%	76,03

Table 3-16: German PV kWh prices with local soft factor change 1992-2003

The results of the experience curve analysis are:

Years 1992-2002: Progress ratio = 83,18% (R^2 = 0,97)
Years 1992-2003: Progress ratio = 82,91% (R^2 = 0,97)

In the final experience curve analysis we will include all soft factor changes into one experience curve. The only constants left are:
c_v = 1,5%
inf = 2%
H_{DE} = 1150 kWh/qm/yr

The table below shows the price development of the PV kWh price:

Year	Cum.Cap. Germany in MW	Cum.Cap. World in MW	Price System D Own in €$_{2000}$/Wp	Lifetime n in yr	PR$_0$	Degra-dation	Imputed Interest k	Price D in €-Cent$_{2000}$/kWh
1992	5,6	372	12,11	17,0	67,5%	0,91%	13,00%	274,4
1993	8,9	432	12,01	17,5	68,2%	0,87%	12,40%	257,11
1994	12,4	501	10,44	18,0	68,8%	0,83%	12,01%	217,03
1995	17,7	579	9,39	18,5	69,4%	0,80%	11,61%	186,72
1996	27,9	668	8,46	19,0	70,2%	0,77%	11,15%	159,91
1997	41,9	793	7,91	19,7	70,9%	0,73%	10,76%	144,54
1998	53,9	948	7,39	20,3	71,4%	0,69%	10,54%	130,71
1999	69,5	1150	6,93	21,1	71,8%	0,65%	10,32%	118,69
2000	113,8	1437	6,60	22,0	72,7%	0,61%	9,93%	107,65
2001	194,7	1828	6,91	23,1	73,7%	0,57%	9,55%	107,32
2002	278	2390	5,76	24,3	74,3%	0,52%	9,32%	86,32
2003	470	3134	4,86	25,6	75,3%	0,48%	9,00%	69,57

Table 3-17: German PV kWh prices with soft factor change 1992-2003

The results of the experience curve analysis are:
Years 1992-2002: Progress ratio local = 81,45% (R^2 = 0,97)
Years 1992-2003: Progress ratio local = 81,18% (R^2 = 0,98)
Years 1992-2002: Progress ratio global = 65,41% (R^2 = 0,95)
Years 1992-2003: Progress ratio global = 65,57% (R^2 = 0,97)

To summarise, all the results of the PV systems experience analysis are shown in the following table:

Year 1992-2003, German PV System and kWh Prices	Progress Ratio Local	Progress Ratio Global
Price PV system[25]	87,26%	75,9%
Price PV kWh with global change		72,25%
Price PV kWh with local change	82,91%	
Price PV kWh with global and local changes	81,18%	65,57%

Table 3-18: Progress ratios of German PV kWh experience curve analysis 1992-2003

The following graph shows the different development of the two experience curves, only PV system prices and PV kWh prices including all soft factor changes, related to local capacities:

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[25] Values here are slightly different to values in Table 3-10 because here the years 1992-2003 were analysed (not 1992-2002) and the cumulative reference was BSi/UVS (not IEA).

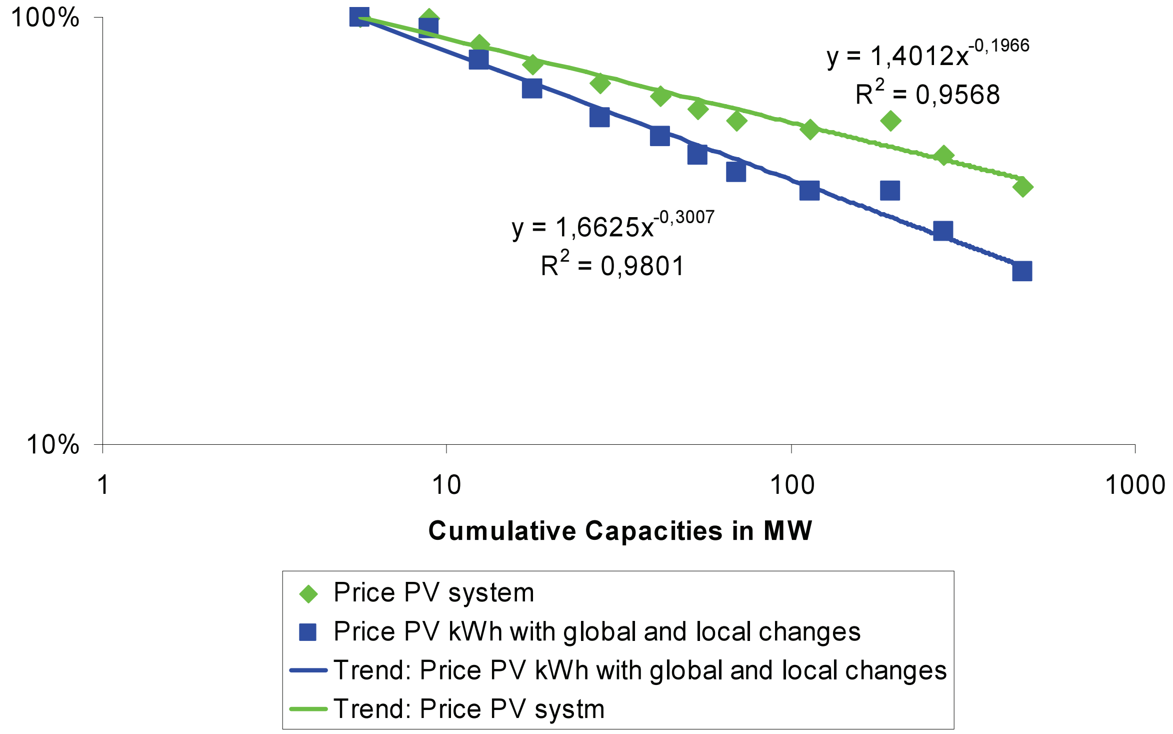

Figure 3-10: Experience curves of German PV system and kWh prices including changing soft factors[26]

Interpretations:

In this section the difference has been shown between type I experience curves for PV system prices and type II experience curves for kWh prices. Due to the different learning systems of the soft factors, the implications of local and global soft factor changes on the kWh price have been presented separately. Including all soft factor changes in one experience curve the progress ratios improved around 6% related to local capacity growth and around 10% related to global capacity growth. It is important to note that both progress ratios overestimate and underestimate some changes in the input variables, due to the big difference in global and local growth in the analysed time frame: The local progress ratio of 81,18% underestimates the price reductions of modules, the extension of lifetime and the improvements in degradation. The global progress ratio of 65,57% overestimates the price decreases of BOS, the improvements of the performance ratio and the decreases of the imputed interest. But even with such difficulties, it can clearly be seen that, when analysing the price development of the kWh PV, the upper limit for the progress ratio improves from 87,26% to 81,18%, which is remarkable. Summarising the results it can be

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[26] For presentation purposes the kWh prices were normalised to the starting values.

concluded that the range of PV system progress ratios of 75,9%-87,3% is lowered to 65,6% to 81,2% for PV kWh prices progress ratios.

3.5.2.4 Extrapolating PV kWh Experience Curves into the Future

It could be seen in the last section that learning of solar energy was remarkably underestimated in the past when only looking at installation or module costs. Even more important is the outlook to the future. As a result of the sensitivity analysis before, it is known that the progress ratio of a type II experience curve is not so easy to use to forecast the future kWh price, due to the different influences of the soft factors. Therefore in the following table for each soft factor the individual learning curve is extrapolated into the future and with these values the PV kWh price is calculated. Because of the local and global learning of soft factors, assumptions of the local and global growth of cumulative capacities must be made. Although the growth rate was very high in Germany in the last years, it is unlikely that this will continue (at least for longer time periods) and therefore German and worldwide growth are assumed to be equally 25% per year until 2010. Furthermore from 2011 to 2020 German growth is reduced to 10% per year while worldwide growth continues with 25% yearly.[27] For the development of the PV system prices the former calculated progress ratio for local capacities of 87,26% was used.[28] With these assumptions future kWh prices are calculated in the next table.

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[27] In this section the main focus is not on different growth rates. The years are just given as a possibility, but only the relationship between global and local growth is important for the PV kWh price calculation. The detailed analysis of different growth rates and their influence on future PV competitiveness is made in the next chapter.

[28] As discussed before this could be seen as a very upper limit of the PV kWh progress ratio. The use of the global progress ratio would also be possible in this analysis and make no difference in the principle significance of the results.

Year	Cum.Cap. Germany in MW	Cum.Cap. World in MW	Price System D Own in $€_{2000}$/Wp	Lifetime n in yr	PR_0	Degra-dation	Imputed Interest k	Price D in €-$Cent_{2000}$/kWh
2003	470	3.134	4,86	25,6	75,3%	0,48%	9,00%	69,57
2004	920	3.917[29]	4,44	26,8	76,5%	0,45%	8,64%	60,37
2005	1.483	4.896	4,04	28,0	77,4%	0,42%	8,41%	52,95
2006	2.186	6.120	3,74	29,2	78,2%	0,39%	8,24%	47,25
2007	3.065	7.650	3,50	30,5	78,8%	0,37%	8,10%	43,05
2008	4.163	9.563	3,30	31,8	79,4%	0,34%	7,98%	39,57
2009	5.536	11.954	3,12	33,2	80,0%	0,32%	7,87%	36,42
2010	7.253	14.942	2,96	34,7	80,5%	0,30%	7,78%	33,84
2011	9.141	18.678	2,82	36,2	81,0%	0,28%	7,70%	31,65
2012	11.218	23.347	2,71	37,8	81,4%	0,26%	7,64%	29,94
2013	13.503	29.184	2,62	39,5	81,8%	0,25%	7,58%	28,38
2014	16.017	36.480	2,53	41,3	82,1%	0,23%	7,53%	27,03
2015	18.781	45.600	2,45	43,1	82,4%	0,22%	7,48%	25,84
2016	21.822	57.000	2,38	45,0	82,8%	0,20%	7,44%	24,81
2017	25.167	71.250	2,31	47,0	83,0%	0,19%	7,40%	23,85
2018	28.847	89.063	2,25	49,0	83,3%	0,18%	7,37%	22,94
2019	32.895	111.329	2,20	51,2	83,6%	0,16%	7,33%	22,13
2020	37.347	139.161	2,14	53,5	83,9%	0,15%	7,30%	21,39
	50.000	186.306	2,02	56,6	84,5%	0,14%	7,23%	19,85

Table 3-19: Values for possible future kWh price development

It can be seen from the results that lifetime and performance ratio are on the increase while degradation and imputed interest are continuing to decrease. The potential error could be calculated which would have resulted when just extrapolating the 81,18% progress ratio of the kWh experience curve from the years 1992-2003. The linear regression returned:

log a = 2,6591, m = -0,3007
Price of kWh (x=50.000): $p_{x=50.000} = 10^{\log a} * x^m = 17,6$ €-$Cent_{2000}$/kWh

When comparing this with the value of 19,85 €-$Cent_{2000}$/kWh from the table above for 50.000 cumulative capacities in Germany an error of 11% is found. This seems relatively small compared to the many cumulative doublings (6,7). Therefore it could be discussed whether the normal extrapolation could also be used with kWh experience curves as an approximation.

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[29] At the time of the analysis this value was also extrapolated, because the extraordinary growth of the year 2004 was still not known.

Results compared to type I experience curve:
The following table shows the price decreases of both PV system price and kWh prices compared to the base year 2003.

Year	Cum.Cap. Germany in MW	Cum.Cap. World in MW	Price System D Own in €$_{2000}$/Wp	Price D in €-Cent$_{2000}$/kWh	PV System Price in %	PV kWh Price in %	Percentage Difference
2003	470	3.134	4,86	69,57	100%	100%	0%
2004	920	3.917	4,44	60,37	91%	87%	5%
2005	1.483	4.896	4,04	52,95	83%	76%	9%
2006	2.186	6.120	3,74	47,25	77%	68%	13%
2007	3.065	7.650	3,50	43,05	72%	62%	17%
2008	4.163	9.563	3,30	39,57	68%	57%	19%
2009	5.536	11.954	3,12	36,42	64%	52%	23%
2010	7.253	14.942	2,96	33,84	61%	49%	25%
2011	9.141	18.678	2,82	31,65	58%	45%	28%
2012	11.218	23.347	2,71	29,94	56%	43%	30%
2013	13.503	29.184	2,62	28,38	54%	41%	32%
2014	16.017	36.480	2,53	27,03	52%	39%	34%
2015	18.781	45.600	2,45	25,84	50%	37%	36%
2016	21.822	57.000	2,38	24,81	49%	36%	37%
2017	25.167	71.250	2,31	23,85	48%	34%	39%
2018	28.847	89.063	2,25	22,94	46%	33%	41%
2019	32.895	111.329	2,20	22,13	45%	32%	42%
2020	37.347	139.161	2,14	21,39	44%	31%	43%
	50.000	186.306	2,02	19,85	42%	29%	46%

Table 3-20: Difference between type I and type II trend extrapolation for German PV Systems

Because of the lower progress ratio of the kWh prices, prices decrease much more quickly. In the last row the difference between price decreases is related to the kWh price for each cumulative capacity. When reaching 10 GW local capacity the difference is 30%, for 25 GW it is nearly 40%. The analysis has demonstrated exemplarily that neglecting the technological learning of the soft factors leads to a remarkable underestimation of future price decreases. In the following figure the results are summarised graphically:

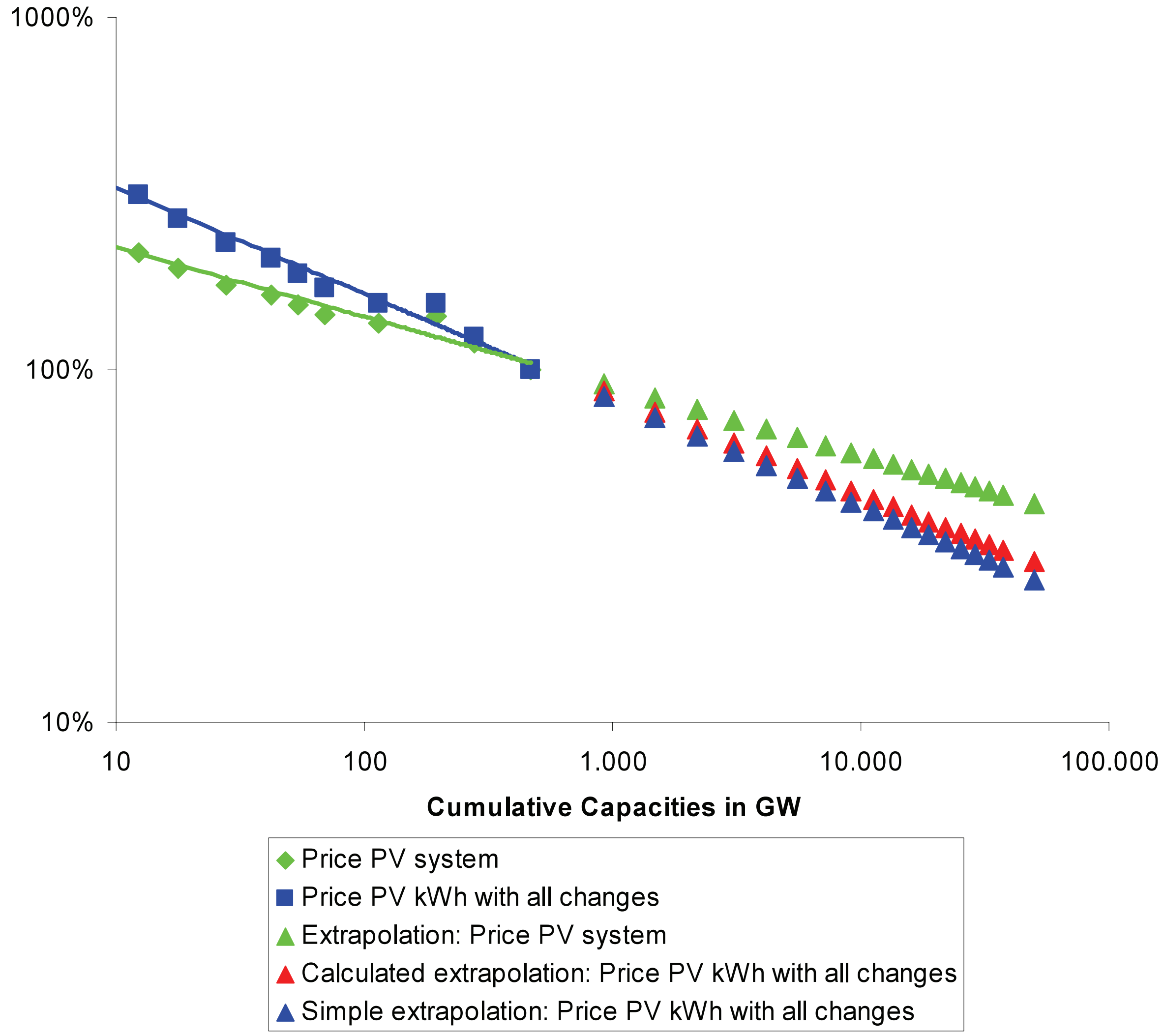

Figure 3-11: Difference between extrapolation for German PV Systems and kWh prices[30]

3.6 Conclusions

Firstly, in this chapter, the concept of kWh experience curve approach has been presented. Secondly, the means of calculating the price of a kWh PV have been explained. After testing the different soft factors concerning their influence on the kWh price the data research on the soft factor development in the past has been reviewed. Finally different experience curves based on kWp prices and based on kWh prices have been constructed and evaluated and an outlook of the extrapolation of experience curves has been given.

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[30] In this graph the kWh price series and forecast have been normalised with the base year as 2003. This shows the difference of past and future development more clearly.

3.6.1 Main Results

In the following the main results are summarised, which are important for the break-even part of this work.

Experience curve including soft factor change return better results:
One of the main goals of the chapter has been to show the difference between using only PV system or module prices or including other soft factors (e.g. system lifetime), which influence the kWh price. The results have shown that there is a remarkable lower progress ratio for kWh experience curves (65,6%-81,2%) than for PV systems experience curves (75,9%-87,3%). The improvement of the progress ratio in this analysis has been between 6%-10%.

Soft factors importance differs considerably:
The absolute value of the price decreases strongly depend on the sensitivity of the soft factors. Soft factors like the imputed interest and the improvement of the performance ratio have very strong influence on the kWh price, whereas others like the module degradation have little influence (see Table 3-1 for a summarisation of the numbers). The improvement potential of some factors is limited, for example module degradation or variable cost cannot be negative. Also important is the interrelationship of the different soft factors. While an extension of the PV system lifetime has little influence on the kWh price assuming a high imputed interest, this changes when using lower imputed interests. Although each factor on its own seems to have little impact, the sum of all factors showed an important improvement in the progress ratio. Nevertheless the installation costs are the dominant input variable in every experience curve analysis.

Characteristics of kWh experience curve extrapolation:
PV kWh experience curves are compound experience curves. The normal trend extrapolation has shown an error of 11% for projected 50 GW cumulative capacities in an exemplarily scenario, because past learning experience of the soft factors would be assumed to happen equally in the future. Instead of continuing the trend of a kWh experience curve, all trends of the single soft factors have been analysed independently and then have been put together. Therefore an important point for the following break-even analysis is, that future extrapolation must be made for each input factor separately and these results can be combined again for a kWh prognosis.

Challenges of global and local learning:
In the past 10 years growth of photovoltaic has been very different within the local

German market and the global market. Thanks to a very favourable renewable energy policy Germany has achieved higher growth rates than the world market in past years (on average 46%/yr for Germany compared to 26%/yr worldwide). For the calculation of the experience curves this brought along some challenges. Learning of the input factors had to be related different to global or local cumulative capacities. This always implies increasing insecurities in the analysis. As recent developments show, many countries are also introducing PV into their energy mix. Therefore the markets not only for modules, but also those for inverters and the rest of BOS are quickly becoming global. It can be estimated that strong growth rate differences between markets will decrease in coming years, simplifying future experience curve analyses. Because of this it has not been the goal to find a unique correct experience curve. On the contrary the diversity of the local and global experience curves that have been presented should clarify the relevance of the assumptions for the results.

Experience curves are made on a highly aggregated level:
In this work there are no different experience curves for the different PV technologies presented. Therefore a shift in technology is only visible on a highly aggregated level. Due to the strong increase of the new PV technologies in the last two years it seems interesting to investigate different experience curves for example for thin film technology when regarding only modules as soon as reliable data can be obtained. Although the cumulative capacities are still very small this may soon change and technologies other than those which are silicon based will gain an increasing portion of the PV market. Then necessary price or cost data may be available as well.

Absolute price of a kWh PV is higher than in other studies:
PV kWh price in this work seems to be higher than in other studies. This depends strongly on the realistic assumptions of the input factors. Using an adequate imputed interest and not neglecting degradation of energy earnings are just two areas where this work differs a lot from other publications. The assumption of the risk-free part of the imputed interest (6%) is especially responsible for the higher price level compared to other studies. It is true that in the last 5 years interest rates for long term investments were historically low (about 4-5%). But for exactly this reason, the very low interest rates of today should not be used in a long-term scenario.

Progress ratios comparable with other studies:
With a progress ratio of about 76% for PV system prices, this value is in the same progress ratio range as the studies mentioned in section 2.2 (74%-80,5%) for modules. But comparing results of different experience curve studies is not easy. Obviously the results depend upon the used time frame and if there were technology

breakthroughs or a period of “price umbrella”. But the difference between type I and type II experience curves and the soft factor relevance has been clearly visible. Including the soft factors a change of the progress ratio to 70%-75% is very probable.

3.6.2 New Developments of PV Prices

In the former sections the majority of the analysis has been made for the time range 1992-2003. This has been caused mainly by the scarcity of reliable price data for the years 2004 and 2005. After the 100.000 roof-top program ended in Germany in 2003, there was no reliable database of installed PV systems available, neither from the government with a central register or by industry associations with a private database. This is a very serious point in the actual discussion because scientists need reliable databases for their research, but so far, because of bureaucratic fears, no decisions have been made. As the new version of the German renewable energy law in 2004 turned out to be a phenomenal success, a worldwide silicon shortage was caused due to the impressive growth of PV (as it was anticipated by some experts [Schaeffer et al. 2004a]). But at the same time the PV industry used the massive demand for PV products to increase prices in 2005 and this year turned out to be one of the most profitable years in PV industry so far. As reliable data of installed PV systems is not available after 2003 only market survey data can be used to describe the price developments. The PV magazine Photon publishes an overview of PV systems offered in Germany every year. The nominal prices for systems over 10 kWp were reported as 4,24 €/Wp for 2004 and 4,72 €/Wp for 2005 [Kreutzmann; Siemer 2005]. A price increase always means that the progress ratio was bigger than 1 in that period of time.

How does this “price umbrella” influence the long term-progress ratios?

In the following table the progress ratio for the German PV system prices are also given for the years 2004 and 2005 with the survey data of Photon related to worldwide growth (Maycock).

Start Year	End Year	Progress Ratio	R^2	Cumulative Doublings
1992	2002	76,20%	0,917	2,7
1992	2003	75,90%	0,941	3,1
1992	2004	75,20%	0,958	3,5
1992	2005	76,82%	0,948	4,0

Table 3-21: Experience curves for German PV system prices years 2002-2005

While the progress ratio is 1% better for the year 2004, where prices reached their minimum so far, compared to 2002, progress ratio increased about 1,6% when including 2005. It may be surprising but the effect on the progress ratio is not very strong. Due to the massive new investment in automation, the extension of PV capacities with new technologies and an overcome of the silicon shortage in 2007 the price should start to decrease again significantly and therefore the progress ratio will also decrease once again.

4 Analysis of PV Competitiveness – The Break-even Analysis

This chapter will analyse the costs and possible profits of an increased use of PV for electricity power production with the help of the results of the last chapter. In the first section the concept of break-even analysis and different types of break-even prices are described. In the second section important literature regarding the topic of break-even analysis is reviewed. The value of PV in the public electricity grid is analysed in section 3. In section 4 the break-even model and different global and local scenarios are described. Also the learning costs and possible profits are presented. The export orientated scenario and the scenario for niche-markets are presented in section 5, while in section 6 the conclusions of this chapter can be found.

4.1 Concept

One of the big advantages of experience curve analysis is the possibility to estimate future price developments of PV depending on the cumulative capacities. Comparing this estimate with the price of other electricity sources; the so-called break-even price (BEP), the necessary break-even capacity and the learning investments can be calculated. As shown in the following figure learning investments are the cumulative difference between the BEP and the experience curve.

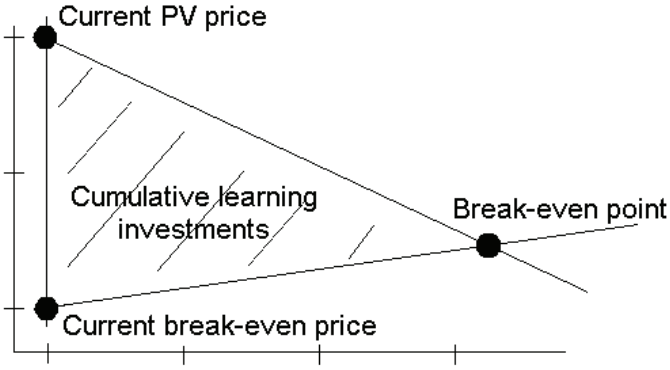

Figure 4-1: Example of the calculation of learning investments[31]

In theory “riding down the experience curve” is a continuous process and it is completely independent from time horizons. In practise the situation is more complicated. First of all it is obvious that the break-even price is not constant over time. As energy resources are scarce, prices increase over the years and therefore the break-even price line is increased. The experience curve reaches the break-even price earlier compared to non increasing break-even prices, which means that less

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[31] Adapted from [Schaeffer et al. 2004a]

cumulative capacities are needed. Because the break-even price level depends upon many different assumptions, it can not be related to only the cumulative capacities. A timeline must be introduced to include changing break-even prices (also for the discounting of future cash flows it is inevitable). In the same instance assumptions of the growth of PV must be made to also relate the cumulative PV capacities to the timeline. This is obviously a disadvantage of introducing changing break-even prices, but must be accepted because no relationship exists between cumulative PV capacities and break-even prices without using the timeline as a reference. It is also needed for the discounting.

4.1.1 Explanation of Terms

As terms such as break-even, learning investment, etc. are often used differently in literature, a short explanation of their meaning in this work is given here.

Break-even (point):
Point in time, where the considered technology (PV) is equally as expensive as the alternative.

Learning investments or learning costs:
In this publication learning investments or learning costs are used equally for the difference between the price of PV and the break-even price. Before reaching break-even the cumulative learning investments increase every year reaching their maximum in break-even. After this the yearly learning costs are negative, because the considered technology is now cheaper than the break-even price and this reduces the cumulative learning costs every year until zero in the year of reaching the win point.

Win point or point of profit:
Point in time where cumulative learning investments are getting negative, which means, that from this point of time, the economy benefits from using the new technology, because all yearly learning investments of the former years were regained.

Difference costs:
In some publications (mostly German ones) difference costs are used instead of learning costs or learning investments.

4.1.2 Different Types of Break-even Prices

For the calculation of the learning costs, on the one hand the run of the experience curve for PV is needed. On the other hand the reference for the calculation, the break-even price, is equally important. As mentioned before many studies do not include changing break-even prices over the years. Mostly this leads to an underestimation of the cumulative learning costs, because a future/higher BEP is used for all years while for the early years at least a lower BEP must be used as reference. But apart from this, the absolute values of break-even prices are assumed quite differently. In the following sub-sections the different approaches are presented and evaluated.

4.1.2.1 Estimated Value

A large number of studies use an estimated value of XX Cents/kWh as the constant break-even price for PV (e.g. 5 Cent/kWh in [Poponi 2003];[Schaeffer et al. 2004a]). With assumptions for capacity factor, life time and imputed interest, etc. break-even prices for modules or systems are calculated. In these studies the assumed kWh value is normally based on actual electricity prices or future assumptions, but without a detailed explanation. It is obvious that it is difficult to discuss whether these assumptions are really reliable when no further explanation is given as to why they are used.

4.1.2.2 Prices of Power Production Plants

Others have the opinion that PV must compete with other power plants, so their price must be considered for comparison. The fossil or nuclear supporters argue that PV can only save fuel costs because PV is not constantly available and therefore has no capacity effects. It could be questioned whether this is true, but nevertheless in their calculation method only variable fuel costs are used as break-even price. These costs are most often estimated at 2-3 Cent/kWh.

If not only variable costs are regarded but the full costs approach is used, it is argued, that PV in the public grid saves energy primarily from the very flexible gas-steam power plants. Therefore their actual and future cost profiles are examined (they depend largely on the gas price and on the assumed costs for CO_2 production). Typical values are in the range of 2-6 Cents/kWh (e.g. [BMU 2005a];[Krewitt et al. 2005a]).

The advantage of the use of cost data from electric power plants would be that fix costs of these plants are quite well known and examined in different studies. The big disadvantages are, that fuel costs are extremely volatile and using mean values does not take into account the specific profile of PV production, which is very high around midday, when energy prices are also higher than average. To avoid this error other authors such as [Zwaan et al. 2004] use cost production profiles of power utility grids and find a mean value for a PV profile of 3,8 Cent/kWh, which lets them also assume a BEP 1 $/Wp, when PV is used in sunny regions. This approach seems more promising because cost production profiles of utility grids are not only dependent on the cost production side, but depend on the demand side profile as well.

4.1.2.3 Power Exchange Prices

Since the deregulation of electricity markets (e.g. in Germany 1998) power exchanges began to play a more and more important role as a price indicator for the market. Although in the earlier years until 2002 the traded volumes were very low and therefore less reliable, this has changed and first studies include the price data of power exchanges in their BEP calculations (e.g. [BMU 2005b];[BMU 2005a];[IZES 2004]). Also with power exchange price data there exists different approaches of finding the value of PV. One could take the base load price, the peak load price or even combine price and PV production profiles, because of a possible correlation between PV production and peak load prices.

Using power exchange prices has a lot of advantages:

- The data base has become very extensive. Not only data of the day-ahead spot market is available, also data for futures[32] can be analyzed. This makes it more possible to include market expectations of future energy price developments in the calculations.
- Because hourly contracts are traded, it is possible to match PV profiles from the past with the price data.
- Due to the fact that CO_2 certificates are also traded, it opens a new possibility of research into how external costs of power production are included in prices.
- Although there can be short term disturbances of the market balance, in the long run the prices of the power exchange will converge to full cost power production prices (if the market prices were different to the production prices for a long time new power plants would be constructed by investors).

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[32] Futures are contracts that are traded today, for a power delivery in the future e.g. the year 2009.

For all these reasons power exchange prices will be used in this work for the break-even analysis of PV.

4.2 Break-even Analysis in the Literature

Apart from the experience curve studies mentioned in section 2.2, there are some more papers that deal with break-even scenarios or break-even prices of PV. Hereafter the most important recent publications are summarised. The numbers of these studies can also be found in the overview in Table 4-3.

4.2.1 [BMU 2005a]

This study was made for the German ministry for environment (BMU) and researches the costs that arise from the increase of renewable energies in the electricity sector due to the EEG (German renewable energy law) up until the year 2020. Here only the important points about the value of PV in the public grid are summarised.

The authors assume a progress ratio of 0,8. The estimation of the German PV market of 600 MW/yr for 2005-2020 (corresponding installed total capacities are 4,1 GW in 2010 and 10 GW in 2020) seems very unrealistic.[33] As un upper limit they assume an increase of the market to 900 MW/yr which corresponds to 13,4 GW installed capacity in 2020 (12,4 TWh/yr). For the value of renewable energies in the public grid the authors distinguish between the “power exchange price based” variant and “cost of power generation based” variant. The second variant is presented with prices which are always below prices of the first variant and the authors use only the power exchange prices in their break-even analysis. On the European power exchange in Leipzig (EEX) the base load was traded on an average of 28,52 €/MWh in 2004 and an average of 43 €/MWh in 2005.[34] As the price premiums for futures are not reasonably higher compared to other markets, this is an indication, that the market is not expecting significantly increasing prices.[35] Therefore the authors assume the following values of PV in the public grid in the “power exchange price based” variant:

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[33] Even for 2004 these numbers are to low (see section 3.4.2.1).

[34] Apart from the increase of the oil and gas prices this was caused by the new CO_2-certificates, which were included in the market prices as opportunity costs.

[35] Futures are contracts for power delivery in future years. The difference between futures and spot prices is also called premium for risk.

Year	Lower Variant in €$_{2005}$/MWh	Higher Variant in €$_{2005}$/MWh
2003/2004	29,00	29,00
2005	43,00	43,00
2010	44,30	49,10
2015	47,00	56,90
2020	48,90	63,40
2025	50,17	68,00
2030	51,44	72,70

Table 4-1: Estimation of future development of base load prices[36]

The high variant assumes increasing prices for CO_2 certificates. The authors admit that not looking at the specific generation profile of PV is a big simplification. Somehow including the proportionate production of peak power would lead to reasonably different results. In the analysis for the costs of renewable energies in the public grid the "higher variant" is used and a second alternative "extern costs" is introduced which leads to another price increase of 0,01 €/kWh. No avoided costs for minor grid usage are assumed. Regrettably there are no explicit numbers given for PV separately, but from a figure it can be estimated, that the payments to solar energy producers increase to more than 1 billion €$_{2005}$ in the year 2010 and to more than 2 billion €$_{2005}$ in the year 2020. This is more than a third of all payments to renewable energies caused by the German Renewable Energy Law (EEG).

Discussion:
It is important to point out, that this study is not really a break-even study. There are no calculations made when PV becomes competitive and what overall costs will occur. The study rather aims to calculate the elevated costs caused by the EEG. This attempt was not really successful and the study was criticised heavily [Witt 2006]. On the one hand costs are underestimated because there is no yearly growth assumed for the German PV market, on the other hand costs are overestimated because of the no-use of PV production profiles and out-dated price data of the EEX.

4.2.2 [Krewitt et al. 2005a]

So far, this study is one of the most detailed break-even analysis' for PV. It researches learning costs on a global, worldwide basis. To undermine certain estimations and assumptions a questionnaire was sent to 5 well-known German solar energy research institutes (e.g. Forschungszentrum Jülich, ISE Freiburg, etc.) and their answers influenced the report. Starting with a literature overview of the development of the worldwide energy consumption and production until the

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[36] Source: [BMU 2005a]

year 2050, 5 scenarios are presented for the different growth possibilities of PV. In 2050 the share of PV of the worldwide electricity production varies from 1% in a very pessimistic case until 39% in an extreme PV favoured scenario (resulting in global cumulative capacities of 289 GW to 8.492 GW). Because PV is used not only grid-connected but also off-grid or in solar home systems, the authors estimate the development of these niche-markets, which have a higher break-even price. These niche-markets are relatively small and account for little more than 10% of the global PV market in 2050, therefore the break-even price depends practically only on the grid-connected PV application.[37] For the calculation of the break-even prices the "cost of power generation based" variant is used. The authors assume that PV will replace electricity of gas-steam power plants. Only fuel costs and capacity factors are used for the calculation, no fixed costs are considered, because PV could not replace other power production capacities. Because the high voltage transmission of PV could be avoided it influences the value of the BEP with 1 Cent/kWh.

In the following table the values of the break-even prices are given for two different scenarios. Scenario A assumes a relatively moderate price increase of the fuel costs and leaves the value for avoided CO_2 constant at 15 €/ t CO_2. Scenario B assumes increasing prices for avoided CO_2 from 20 €/ t CO_2 in 2020 to 50 €/ t CO_2 in 2050.

Year	**Scenario A €$_{2004}$/kWh**	**Scenario B in €$_{2004}$/kWh**
2004	0,067	0,067
2010	0,069	0,069
2020	0,071	0,074
2030	0,078	0,082
2040	0,081	0,091
2050	0,087	0,101

Table 4-2: Break-even prices for PV[38]

In their study the authors include an interesting examination of the material requirements and possible lower cost limits for PV because of material costs. To reach their goal of a PV system price of 1 €/Wp the production costs of a module must decrease to 0,50 €/Wp, which seems possible in the long run, but not before 2025-2030 in the best case scenario because of the technological advances that have to be reached.

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[37] Even a doubling of the niche-markets to 20% share would raise the break-even price by only 5%.

[38] Source: [Krewitt et al. 2005a]

Regarding the break-even analysis, 3 different scenarios for the development of the progress ratio are combined with growth scenarios. While in the first scenario the progress ratio stays constant at 0,8 in the other scenarios it increases over time. For each scenario the authors give the time when break-even will be reached, the cumulative learning cost until reaching break-even and the cumulative learning costs until the year 2050 and 2020.

The main results of the break-even analysis are that progress ratios should not be above 0,8 until the year 2020, that learning cost until reaching break-even can be between 280 and 360 billion € when assuming a considerably growth of PV. Compared to the cost of electricity generation this would be a surcharge of only 0,1-0,2 Cent/kWh. If the PV share of electricity production should still be under 5% in the year 2050, it will be very unlikely for PV to reach the break-even point.

Discussion:
This study gives a broad overview of the possible developments of the learning costs of PV riding down the experience curve. Although the approach of interviewing experts for the estimation of possible future PV developments is very helpful, in the break-even analysis there are a few points to challenge. Assuming changing progress ratios over time in the break-even analysis is a questionable method as, on the one hand the progress ratio should be related to the cumulative production and on the other hand there is no evidence given as to why progress ratios must decrease in maturing industries. The calculation of the cumulative learning costs is done without discounting future cash flows (this implies that one Euro in 2050 has the same value as in 2005). This is not common in economic science because the relevance of future cash-flows is overestimated. In the break-even analysis of this work therefore a main aspect is laid on the correct discounting (see section 4.4.2.4 for details). Through their assumption, that niche-markets are not able to increase their share of worldwide PV installations, the possibility of using PV in markets with higher break-even prices does not have a countable effect. This assumption must be strongly doubted and in section 4.5.2 the niche-market scenario of this work is presented.

4.2.3 [Hoffmann et al. 2004]

This conference paper gives a short overview of the history and future of the PV solar electricity market. This paper is not an extensive break-even analysis but it is quoted in other publications (e.g. [EPIA 2005]) and therefore briefly presented here.

One of the sections deals with the costs of introducing a European wide feed-in tariff similar to the German EEG. The author does not give any estimates of future developments of cumulative capacities on a world-wide basis. He estimates the market potential for Europe and assumes a yearly price decrease of 5% until 2020 and payments for 20 years system lifetime until 2040. Without discounting future cash flows the total costs for the PV payments are given as 326 billion Euros. It is proposed to use as the break-even price the end-consumer price of 17 Cent/KWh which normally would have to be paid to the local electricity utility, assuming increases of 1%/year. The total amount of the learning costs is not given, but the break-even point will be reached in the year 2030 and in the year 2040 only 13 billion Euros are not regained from the former learning investments.

Discussion:
The numbers presented in this paper can not be reproduced because many variables are not given (detailed development of the cumulative installations, assumed prices, etc.). There are many important points to be criticised: No discounting of future cash flow is done. The break-even price includes not only the price of electricity production and transportation, but includes taxes etc. as well and can not be related to the cost of PV electricity production without taxes. Just looking at Europe neglects completely the influences of the world wide growth of PV on the break-even price. These points lead to the conclusion that the presented learning investments are not reliable and more extensive research is necessary.

4.2.4 Overview of Break-even Analysis in Literature

In the following table the results of the former publications (including papers of section 2.2) are summarised and the key values are shown. This should give an overview of the research that has been done in the field of PV break-even analysis up to now. Because of the different assumptions of the papers, it is difficult to compare them directly with others.

Author	Progress Ratio	Break-even Cum. Cap. in GW	Break-even Year	Growth Rate	Break-even Price per Wp	Break-even Price per kWh	Learning Inv. in bn
IAE (2000)	78%	150			0,5$/Wp	n.a.	40 $
	80%	200	2025	15%	0,5$/Wp	n.a.	60 $
	82%	600			0,5$/Wp	n.a.	120 $
Zwaan, Rabl (2002)	70%	23	n.a.	n.a.	1,0$/Wp	0,04$/kWh	15 $
	75%	48	n.a.	n.a.	1,0$/Wp	0,04$/kWh	27 $
	80%	148	n.a.	n.a.	1,0$/Wp	0,04$/kWh	64 $
	85%	957	n.a.	n.a.	1,0$/Wp	0,04$/kWh	288 $
	90%	39700	n.a.	n.a.	1,0$/Wp	0,04$/kWh	7110 $
Poponi (2003)	80%	1440	2026-2045	30%-15%	0,9$/Wp	0,05$/kWh	n.a.
	80%	27	2011-2017	30%-15%	3,2$/Wp	0,15$/kWh	n.a.
	85%	67	2015-2023	30%-15%	3,2$/Wp	0,15$/kWh	n.a.
	90%	409	2021-2036	30%-15%	3,2$/Wp	0,15$/kWh	n.a.
Photex (2004)	70%	n.a.	2025	20%	0,7 €/Wp	0,05 €/kWh	89 €
	75%	n.a.	2031	20%	0,7 €/Wp	0,05 €/kWh	193 €
	80%	n.a.	2039	20%	0,7 €/Wp	0,05 €/kWh	634 €
	85%	n.a.	2053	20%	0,7 €/Wp	0,05 €/kWh	5193 €
	70%	n.a.	2006	20%	4,0 €/Wp	0,20 €/kWh	2 €
	75%	n.a.	2008	20%	4,0 €/Wp	0,20 €/kWh	3 €
	80%	n.a.	2009	20%	4,0 €/Wp	0,20 €/kWh	5 €
Krewitt (2004)	80-95%	~1500	2028	30,7%-2,8%	n.a.	0,08 €/kWh	297 €
	80-95%	~ 900	2032	29,7%-3,3%	n.a.	0,08 €/kWh	360 €
	80-95%	~ 550	2042	27%-2,8%	n.a.	0,09 €/kWh	401 €

Table 4-3: Overview of discussed BEP scenarios[39]

4.3 The Value of PV or Break-even Price Calculation with Power Exchange Price Data

Despite the aforementioned different approaches for PV break-even prices, the discussion of the value of PV is still beginning (compared to the discussion about the value of wind energy). It could be seen, that there are many different opinions for the value of a kWh PV in the public grid. To help to advance this discussion process, it is necessary to rely on a broad data basis. In this thesis therefore an economic evaluation of the value of PV is presented, which relies on the analysis of data from the European Energy Exchange (EEX) and of more than 1.000 PV installations in Germany monitored by the company Meteocontrol GmbH. Analysing these two detailed data sources helps to understand the value of PV, which will then be used in the break-even analysis.

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[39] [BMU 2005a] is not mentioned in the table, because it is not really a break-even analysis. [Hoffmann et al. 2004] is not mentioned in the table, because of the scarcity of data.

4.3.1 Data of the European Energy Exchange (EEX)

In July 2002 the European Energy Exchange of Frankfurt merged with the Leipzig Energy Exchange and the headquarters moved to Leipzig. This was necessary because before, both power exchanges could not work profitably. Since then the volumes have increased continuously to 602 TWh in 2005 traded on the EEX Spot and Derivatives Market, compared to 397 TWh in 2004.[40] The volume of the Spot Market also increased from 60 TWh in the year 2004 to 85,7 TWh in 2005, which corresponds to approximately 17% of the total annual electricity consumption in Germany. A study from 2004 of the electricity power trading market showed that the EEX is clearly a market leader compared to other European power exchanges ([Koch et al. 2004]). In the course of the year 2005 the number of trading participants increased from 123 to 132 companies from a total of 16 countries. Generally there must be a differentiation between the Spot Market, which is a day-ahead market, and the Derivatives Market (also called Future Market), where contracts for future months or years are traded. Both markets will be analysed in more detail in the following subsections. Also a look at the market for CO_2 allowances will be made, because it plays an important role with including external costs in the electricity price. In the public discussion, especially in the year 2005/2006 in Germany there were a lot of rumours and assertions of whether price findings at the EEX were really fair or if markets were manipulated by the four big electricity companies.[41] Because the four biggest electricity companies in Germany own between 70-80% of the installed production capacities, the market is very concentrated. This topic will be discussed in subsection 4.3.1.4.

4.3.1.1 Spot Market – Electricity Prices Today

As mentioned above the traded volume of a power exchange is important to estimate the relevance of the prices for the general market. The EEX Spot Market volumes have increased steadily over the years as well as in absolute numbers as a percentage of the German total annual electricity consumption.

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[40] All data of the EEX mentioned in this work is available at the website http://www.eex.de and therefore is not quoted again each time used.

[41] See for example:
F.A.Z., 08.07.2005, Nr. 156 / Seite 13: Industrie hält die Strombörse für einen manipulierten Markt
http://www.faz.net/s/RubD16E1F55D21144C4AE3F9DDF52B6E1D9/Doc~E327FCE8315384524ADE05426D2F11833~ATpl~Ecommon~Scontent.html

Year	Volume in TWh	% of Total Annual Consumption
2003	49	10%
2004	60	12%
2005	85,7	17%

Table 4-4: EEX Spot Market volumes 2003-2005

With 17% of the total annual consumption traded at the EEX in 2005 a new record was reached and the importance of the prices of the Spot Market for the economy is obvious. Therefore the numbers of the EEX are very well suited to use for the evaluation of the actual value of PV in the public grid. The Spot Market of the EEX is a so called day-ahead market, where at 12 o'clock an auction is held for the electricity delivery of the following day (or the following 3 days on Fridays). Spot contracts can be divided into hour and block contracts (e.g. a block contract is "Morning 07-10"). In the following figure the average prices for each hour are shown.

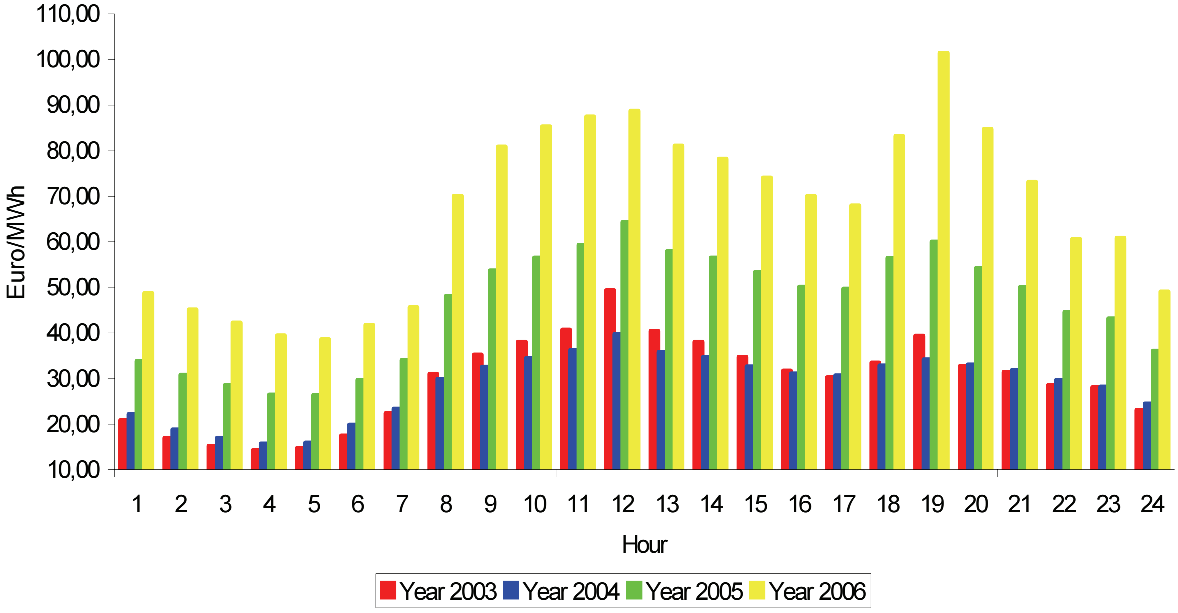

Figure 4-2: Hourly EEX prices 2003-2006[42]

It is obvious, that there are big price differences between peak periods (e.g. from 11-12 and 18-19 hours) and night hours, where electricity prices cost less than half those of peak power prices. It is very interesting that the profile of the prices also changed becoming higher during the evening peak. The absolute level of the prices increased a lot in 2005 and at the beginning of 2006.

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[42] In all figures and calculations data of 2006 is included only until the 13th of March 2006

Two important indices of the EEX are the Phelix Base (Physical Electricity Index), which is the hourly weighted average price per day for the hours 1 – 24, and the Phelix Peak, which is the hourly weighted average price per day for the hours 9 – 20. The next graph shows the development of the Phelix Base with a 7-day average to eliminate the weekday/weekend fluctuations.

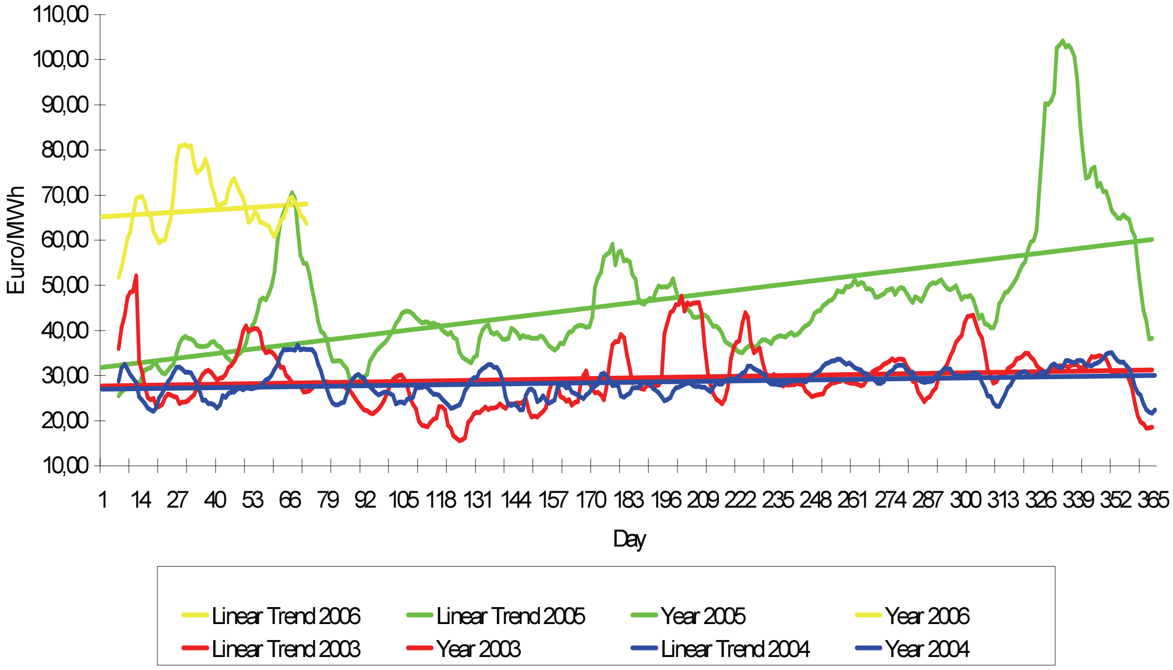

Figure 4-3: Phelix Base 2003-2006 (7-day average)

Again the strong price increases of the years 2005 and 2006 are clearly visible. On average, the Phelix Day Base amounted to 45.98 €/MWh during the year 2005 compared to 28.52 €/MWh during 2004. Although the years 2003 and 2004 do not show big differences, in the summer of 2003 there was a significant peak of more than 40 €/MWh. Due to the very hot summer some power plants had to reduce their output. In 2005 the months February and March were very cold which was responsible for the price peak in these months. The summer of 2005 was again very hot and missing cooling water was responsible for the reduced energy output of nuclear power stations. In the very cold November/December months of 2005 the prices increased a lot because of the strong increasing demand, which had to be covered with high price gas power plants.

Year	Phelix Base in €/MWh	Phelix Peak in €/MWh
2003	29,49	37,00
2004	28,52	33,99
2005	45,98	55,99
2006 (until April)	66,60	81,93

Table 4-5: EEX Phelix Base and Peak averages 2003-2006

But beside these temperature caused effects, most market participants see the reasons for the price increases in 2005 and the beginning of 2006 as stemming from greatly increased fuel costs and in the CO_2 allowances, which have been required since the beginning of 2005. The sub-section 4.3.1.2 will deal with this topic in detail.

Naturally there are price differences between weekends and workdays. For the value of solar energy an effect could be noticed if sunny days fall increasingly on weekends or workdays, but variations are predicted to be balanced over the year.

4.3.1.2 CO_2 Allowances – External Costs of Fossil Energy Production

Since the beginning of the year 2005 CO_2 allowances are necessary for all big energy consumers in the EU. In the allocation plan for Germany for the years 2005-2007 the amount of allowances applied for exceeds the maximum budget set by the legislators of 1.485 million allowances (495 millions of allowances per year, 390 millions of allowances corresponding to energy production) [DEHST/UBA 2005]. The budget is exceeded by 14,1 million tons per year or by 2,8%. To meet the maximum budget certain allocations are subject to a proportionate adjustment.[43] It is very important to emphasize that in this first allocation plan the allowances were given for free to the consumers. There are only some organizational fees to be paid by the participants, but generally the CO_2 allowances did not cause any financial burdens for the recipients. The idea behind this was, that during the beginning of the implementation of the CO_2 allowances the industry should not suffer damages due to new costs.

Since March 2005 CO_2 allowances have also been traded at the EEX. The total traded volume of 2,75 million tons in 2005 (0,5% of the yearly maximum budget) was still very small even compared to the reduction obligation of 2,8%. From the traded

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[43] In addition to the proportionate adjustment according to § 4 (4) ZuG 2007 there are also obligations for the participating sectors to reduce their emissions. Detailed information is available at the website http://www.dehst.de

volumes of the first three months in 2006, the yearly trade volume in the whole of the year 2006 can be estimated and should reach between 1,5-3% which would be a remarkable increase. In the following graph the prices for the CO_2 allowances are given with the Phelix Base prices on the second y-axis.

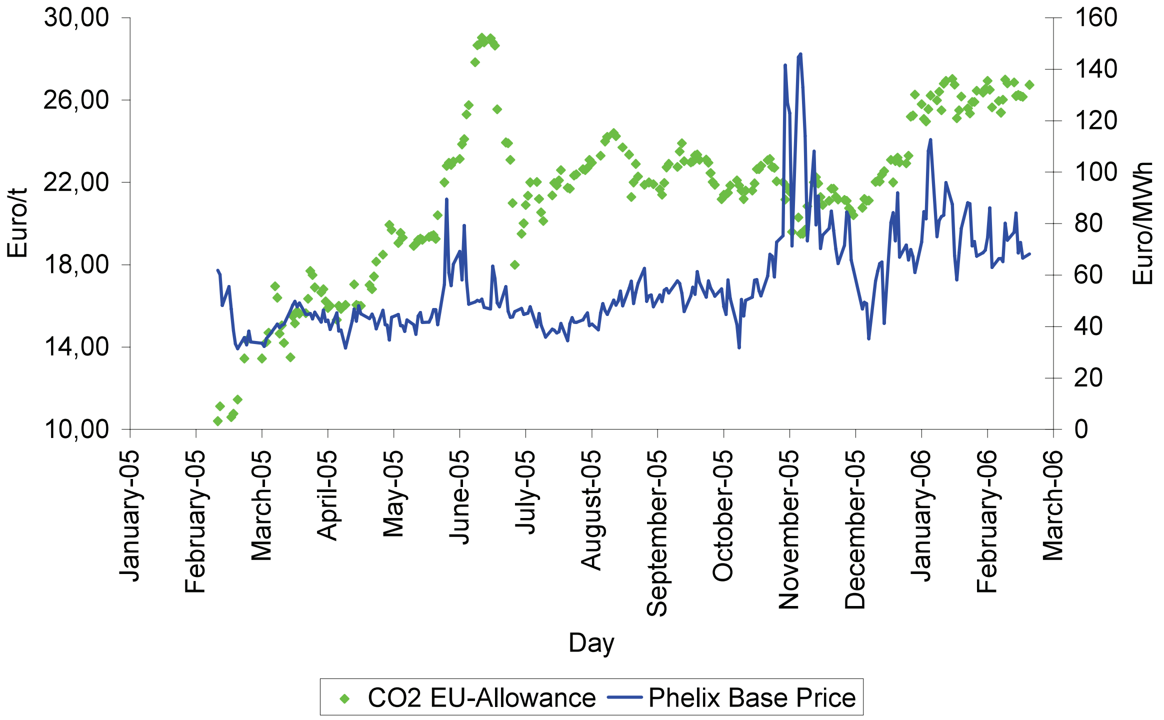

Figure 4-4: CO_2 allowances and Phelix Base 2005-2006

It can be seen that both prices are possibly interrelated, although there were some peaks of the allowances in summer 2005 and of the Phelix Base prices in November/December 2005 because of the reasons mentioned above. The possible correlation can be seen as well in the linear regression graph below.

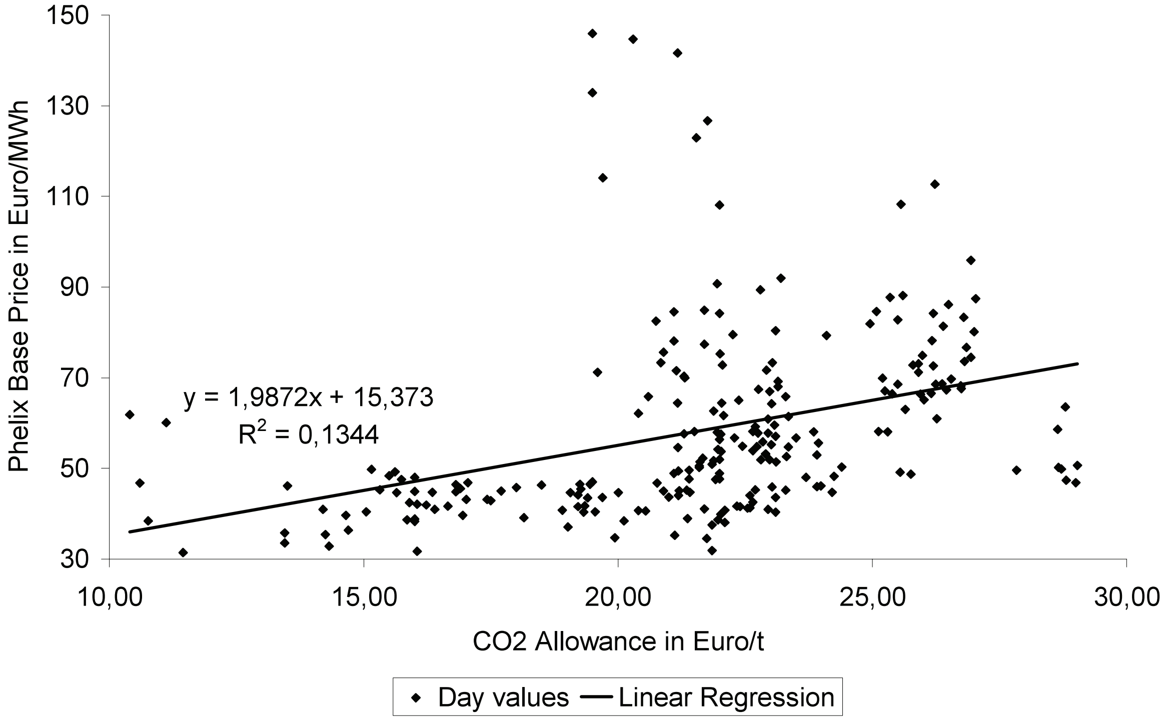

Figure 4-5: Linear Regression for CO_2 allowances and Phelix Base Prices

For the examined period from March 2005 to March 2006 every price increase of the allowances of 1 €/ton corresponds to a price increase of the Phelix Base price of nearly 2 €/MWh. The correlation coefficient is 0,367.

Could the CO_2 allowances be one of the reasons for the increasing electricity prices? Yes, this can be confirmed. Although the CO_2 allowances were given for free to the energy producers in the first allocation plan for the years 2005-2007, the usage of the CO_2 allowances causes opportunity costs. When using the CO_2 allowances a possible profit of selling them is lost. That is the reason why CO_2 allowances are relevant for cost calculations of the energy producers and therefore relevant for the selling price as well, even though they were given for free (see Figure 4-6).

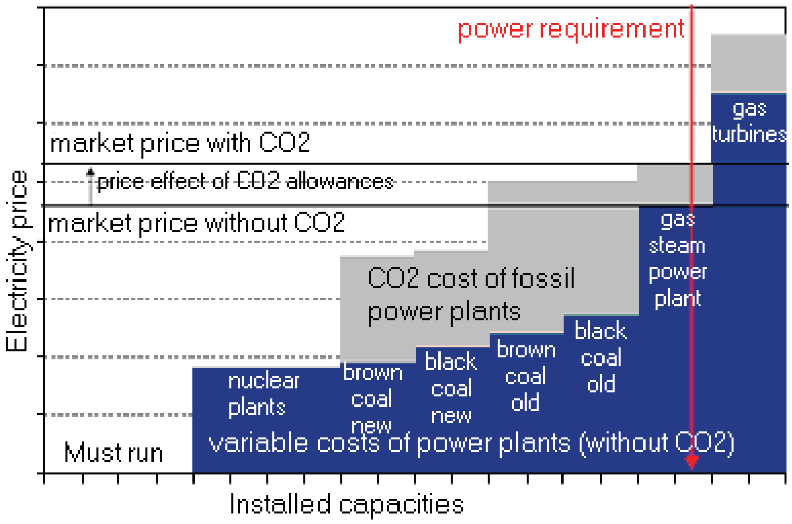

Figure 4-6: Price relevance of CO_2 allowances[44]

External Costs of fossil energy production:
Basically the introduction of CO_2 allowances should be welcome because it supports the idea to include external costs of fossil energies in the electricity price. The error from the consumers point of few was only that the price increases turned out as windfall profits for the electricity companies while an auction of the CO_2 allowances at the beginning would have increased the government's revenues. Apart from the advantages that auctions always have; they are fair, unbureaucratic, transparent and avoid economic disincentives, they would favour solar technologies, because no allowances are needed for PV.

The value of external costs of fossil energy production in literature reaches from 15 €/t to 300 €/t [Krewitt et al. 2005b], which means a difference of factor 20 and underlines the high insecurities of the studies. [Krewitt et al. 2005b] give 70 €/t as best estimate of the value, which is still much higher than the actual price. Although this indicates that still not all external costs are included by the market in the electricity price, in this work no extra surcharge for external costs is made to avoid double counting. It is conservatively assumed that the increased electricity prices since the introduction of the CO_2 allowances reflect sufficiently the inclusion of external costs.

4.3.1.3 Futures – Electricity Prices of the Future

At the Derivative Market of the EEX Futures are also traded. Futures are contracts for

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[44] Adapted from [KRdL/BMU 2006]

power delivery in a certain future time period (month, quarter, year). The volumes of futures traded at the EEX are in total higher than the volumes of the Spot Market, because market participants try to hedge future energy demands to achieve the lowest costs. Therefore the Futures could be used as the market price expectations of future energy prices. The long term Futures for the 2010-2012 are traded on very low volume in contrast to the near term Futures. The following graph shows the Future prices as they were on the 04.11.2006.

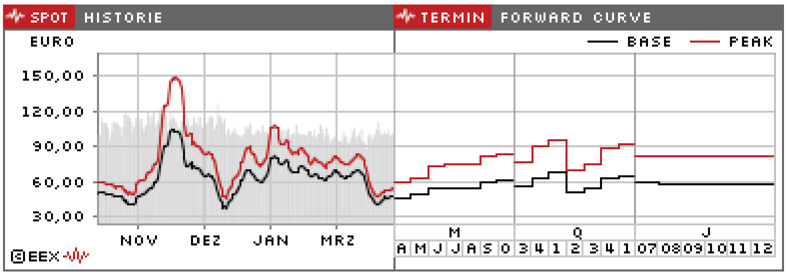

Figure 4-7: Prices of Futures at the EEX (April 2006)[45]

It can be seen that the market expects a price increase for the entire year 2006, while for the second quarter of 2007 lower prices are expected. Looking at the yearly Futures virtually constant prices for all traded years are expected (59,00 €/MWh for Phelix Baseload and 82,50 €/MWh for Phelix Peakload). Comparing this with the average values for 2005 (45,98 €/MWh / 55,99 €/MWh) it can be seen that market participants calculate increasing prices for 2006 and a remaining high level of prices in the following years. As shown above this also may depend a lot on the development of the CO_2 allowances prices and is just the status quo for April 2006.

4.3.1.4 Is there Perfect Competition in the Electricity Market?

Because of strongly increased electricity prices for 2005/2006 in Germany the question is raised whether competition in the electricity market actually exists? There are some strong indications that support the theory that the absence of competition in the German electricity market is another main reason for the strong price increase in 2005 and 2006 [VIK 2006]:

- The electricity price increased a lot more quickly than fuel costs
- The 4 big power generation companies in Germany own nearly 90% of the generation capacities
- RWE produces over 80% of their power for full costs of 24 €/MWh

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[45] Source: http://www.eex.de

- Power companies withdraw capacities and do not offer them at the market although prices would be competitive.

Therefore the VIK (Verband der Industriellen Energie- und Kraftwirtschaft e.V.)[46] has filed a complaint at the German Antitrust Division the results of which are expected in 2007. As increasing prices always invite new competitors to enter the market and prices of the Futures indicate high price levels for the next years, the first big energy consumers in Germany are planning to start with their own energy production and also municipal utilities are increasing their own production again.[47] On the other hand it can be estimated that around 40.000 MW of capacities will be shut down until the year 2020 in Germany due to old plants and exit of nuclear power energy production [Peek 2005]. This means that a big effort must be made to replace these capacities, but nevertheless the trend for increasing or high electricity prices is very likely to continue in the future.

Comparison of EEX prices with other power exchanges:
For at least the years until 2005 it can be seen that the price development of the EEX was not very different from that of other European power exchanges and if there were any differences, they existed for obvious reasons. For example in the year 2004 (2005) the yearly average of the Spot Market prices were 28,13 (46,65) €/MWh at the Powernext in France, 28,59 (46,57) €/MWh at the EXAA in Austria and 28,92 (29,33) €/MWh at the NordPool in Norway compared to 28,52 (45,98) €/MWh at the EEX [Rahn 2005];[Rahn 2006]. The APX in Netherlands normally has a higher price level 31,59 (52,38) €/MWh due to the missing base power capacities and the limit transfer capacities between Germany and Netherlands. Another publication from Peek, which analyzes the years 2001-2005 up until July comes to similar conclusions [Peek 2005]: The price level of the German EEX is, in comparison, below the European average. The price development at EEX, Powernext and EXAA is also very similar. The power exchanges of Italy (IPEX) and Spain (Omel) have higher price levels due to the limited transmission capacities. Prices at Nordpool are also more or less uncoupled from the German development, because of the strong dependency on water power. At least, until the middle of the year 2005 it can be asserted that German electricity prices are not extremely high, nor manipulated by the 4 big electricity companies.

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[46] http://www.vik.de

[47] http://www.atkearney.de/content/presse/pressemitteilungen_archiv_detail.php/id/49297/year/2005

4.3.2 Data of PV Production from Meteocontrol

Thanks to cooperation with Meteocontrol GmbH[48] in this work the PV production data from more than 1000 PV installation in all Germany were available for examination. The data had been logged online over the internet and the database was examined in detail and tested for plausibility. The following PV systems had to be excluded:

- The data set was not complete for all the year (e.g. because the system started working in the analysed year or had major breakdowns).
- The PV system had no calibrated electricity meter
- The PV system had no irradiation sensor

The hourly PV production data of 10,5 MW PV systems for the year 2005 categorised by the number of the postal code remained within the database.

In the following table the distribution of the PV systems is given:

Postal Code	Installations in kWp
1	33
2	102
3	144
4	231
5	63
6	68
7	946
8	2.900
9	6.019
Total	10.506

Table 4-6: Distribution of PV systems by postal code

It can be seen that about 80% of the installations are from the south of Germany. Due to the higher irradiation (and a general compensation by the EEG) this represents the actual imbalance.

In the year 2005 these installations had the following energy output:

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[48] http://www.meteocontrol.de

Postal Code	Energy Output in kWh/kWp
1	859
2	1001
3	951
4	953
5	954
6	1012
7	981
8	1048
9	1092
Weighted Average	1062

Table 4-7: Energy output 2005 in kWh/kWp by postal code

Again, it is visible here that the higher irradiation of the south returns in relatively high energy yields of more than 1000 kWh/kWp for the Postal Codes 8 and 9.

The following table shows the electricity production on a monthly basis:

	Postal Code								
Month	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**Average**
1	22	43	33	33	29	23	24	30	12	29
2	41	39	29	43	37	26	34	38	31	39
3	90	94	85	89	80	63	79	82	72	90
4	117	110	98	107	103	102	105	106	118	113
5	157	132	122	130	120	130	125	130	112	145
6	168	143	144	142	129	142	136	146	129	157
7	138	122	119	123	117	123	119	126	102	131
8	124	112	116	116	101	109	104	117	104	119
9	111	103	99	107	102	97	107	106	87	107
10	83	83	78	74	89	72	79	72	59	82
11	24	37	40	29	31	25	28	32	23	30
12	17	30	19	19	15	10	12	16	9	21
Sum	**1092**	**1048**	**981**	**1012**	**954**	**923**	**951**	**1001**	**859**	**1062**
Month 3-10	**90%**	**86%**	**88%**	**88%**	**88%**	**91%**	**90%**	**88%**	**91%**	**89%**

Table 4-8: Monthly Energy output 2005 in kWh/kWp by postal code

The months March to October produce nearly 90% of the total years production. This implies that the value of PV will not profit from high energy prices in winter times. Further examinations were also made of the database, e.g. the daily distribution of PV power production, but these results are presented in the next sub-sections.

4.3.3 Combination of EEX and Meteocontrol Data

The goal of this section is to find the value of the PV at the EEX in 2005. Combining the hourly price data from the EEX with the hourly production data of the PV systems it is possible to calculate the value of PV for the year 2005 ex post. As described before, normally price settlements at the EEX are fixed at the spot market at midday before the day of delivery. This approach therefore includes a simplification compared to reality. But in this analysis the emphasis is not laid on a practical solution for real trading of solar power at the power exchange. It should be demonstrated which value the PV power production has for the economy, because it replaces other energy sources traded at certain price level. In the section 4.3.3.2 the analysis shows the value of PV compared to the base load or peak load prices and thus helps to clarify the discussion of what price level should be used for the evaluation of PV energy. The correlation between the PV power production and the EEX prices is further researched in section 4.3.3.3.

4.3.3.1 Value of PV Energy at the EEX in 2005

In the following table the results for the hourly weighted PV production prices are given:

Postal Code	Value of PV in €-Cent/kWh
1	5,36
2	5,23
3	5,28
4	5,22
5	5,33
6	5,42
7	5,36
8	5,36
9	5,34
Weighted Average	5,34

Table 4-9: Value of PV at the EEX in the year 2005 by postal code

The weighted average returns a value of PV in the public grid of 0,0534 €/kWh. The results show a surprisingly low standard deviation (0,0667) between the different postal codes. This means that looking at the whole year 2005 there are no big differences of the value of a kWh PV between the north and the south of Germany.

4.3.3.2 Value of PV compared to Phelix Day Base and Phelix Day Peak

Compared with the average Phelix Day Base of 4,60 Cent/kWh for the year 2005 the average PV value is about 16% higher and compared to the Phelix Day Peak of 5,60 Cent/kWh about 4% lower. This result is quite interesting: Why is the average value of PV lower than the Phelix Day Peak which is the average of the hours 9:00 to 20:00?

To examine the reasons for this somehow surprising result a more detailed monthly analysis of the value of PV was made. The goal was to analyse the deviation of the average value of PV (all Germany) each month from the base and peak load prices:

Month	PV Average in €-Cent/kWh	PV Minimum in €-Cent/kWh	PV Maximum in €-Cent/kWh	Base Load in €-Cent/kWh	% Average over Base	Peak Load in €-Cent/kWh	% Average over Peak
1	3,35	3,11	3,46	3,08	8,6%	3,57	-6,3%
2	4,79	4,60	4,98	3,96	21,0%	4,66	2,8%
3	5,39	4,34	5,54	4,52	19,3%	5,42	-0,6%
4	4,63	4,54	4,75	4,02	15,1%	4,58	1,0%
5	4,42	4,36	4,50	3,78	16,8%	4,32	2,3%
6	6,20	6,12	6,67	4,67	32,8%	5,88	5,5%
7	5,49	5,46	5,59	4,53	21,1%	5,37	2,2%
8	4,66	4,63	4,78	3,82	22,2%	4,53	2,9%
9	5,90	5,75	6,04	4,82	22,4%	5,79	1,9%
10	5,83	5,52	5,91	4,75	22,7%	5,64	3,4%
11	7,30	6,50	7,53	6,96	4,8%	9,33	-21,8%
12	8,20	7,47	8,80	6,26	31,0%	8,12	1,0%

Table 4-10: Monthly value of PV and deviation from EEX prices 2005

First of all it is clearly visible that the value of PV does not differ a lot in the different postal code areas of Germany. This result on a monthly basis is equal to the former analysis on a yearly basis. The standard deviations between the different postal codes are quite low; between a minimum of 0,041 in August and a maximum of 0,452 in December. The following graph visualises the numbers from the table above comparing the average value of PV of each month with the Phelix Day Base or Phelix Day Peak:

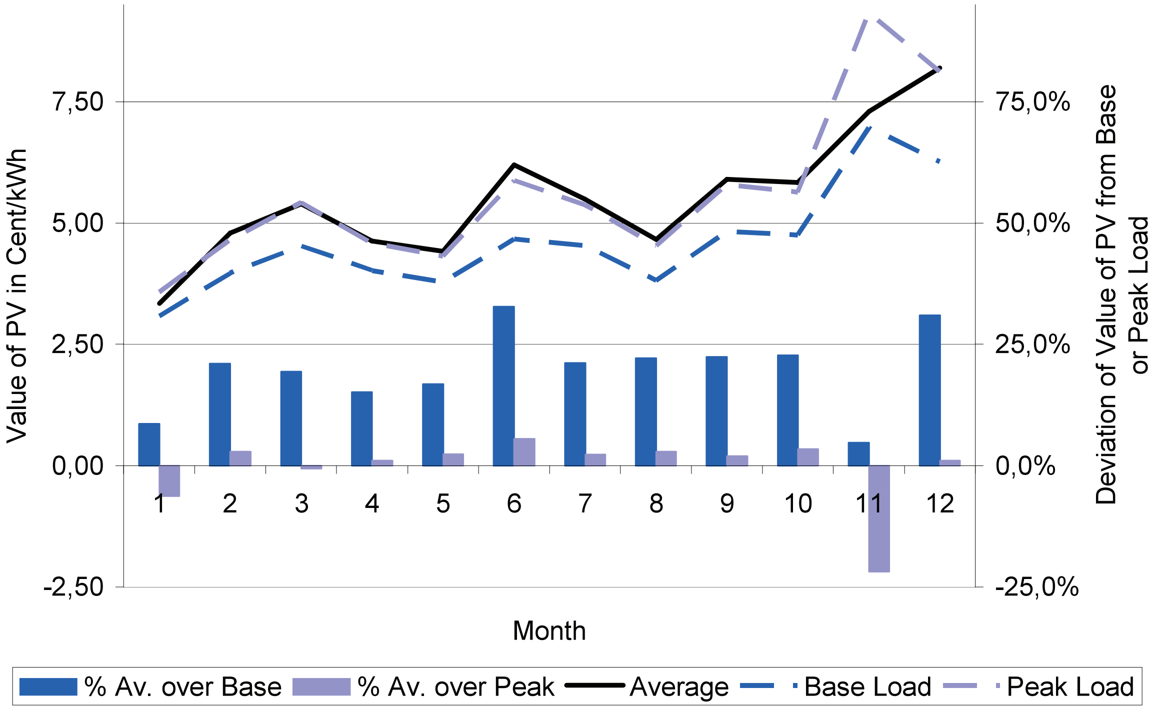

Figure 4-8: Monthly value of PV and deviation from EEX prices

The correlation between the monthly average PV value and the base load and the peak load prices can be seen perfectly. The correlation coefficients are 0,942 for the base load and 0,932 for the peak load. But there is an exception in November 2005. In this month both Phelix Base and Phelix Peak prices exploded, due to the biggest blackouts of electricity in German history. Calculating the correlation coefficients without the value of November the situation improves significantly to 0,991 for base load and 0,995 for peak load. The reason why the value of PV did not follow the price increases at the EEX in November in the same way as in other months was, that in November in Germany after 5 p.m. no PV electricity production is possible. Prices at the EEX always have a second peak between 5 p.m and 8 p.m. (see Figure 4-2), which normally is below the peak of the midday, but in November 2005 these prices were extremely high at these hours of the day and no solar energy could be produced.

If excluding the two best and two worst values from the analysis; because they are regarded as abnormal situations, the average monthly PV value is 20% higher compared to the Phelix Day Base and 2% higher compared to the Phelix Day Peak. It would also be interesting to make the same analysis for earlier years, but in this case the PV production data of 2005 can not be used with price data for other years, because errors will occur due to different daylight-saving times, correlation of hot weather periods and energy prices, etc.. Although an average mark-up of 20% (2%) to the Phelix Base (Peak) price would lead to a value of PV of 5,52 (5,70) Cent/kWh, these values will not be used instead of the weighted average value of 5,34 Cent/kWh, which was the original true value, if every kWh PV produced would have been sold to the public grid for the hourly power exchange prices.

4.3.3.3 Correlation of hourly PV Production 2005 and EEX prices

To ascertain the value of PV in the public grid the hourly correlation of PV production and electricity prices are important. PV production obviously depends on irradiation. EEX prices depend on the supply and the demand of electricity. On the supply side high temperatures can have a negative influence, when power plant production must be decreased due to increased temperature in rivers (as for example happened in the summer of 2003). On the demand side high temperatures also have a negative impact because of increasing demand for air conditioning and cooling applications. But also very low temperatures in winter times are responsible for an increasing demand and increasing prices (e.g. winter 2005/2006). The question therefore is raised of how the PV production profile correlates with the EEX prices. In the following graph the daily distribution of PV power production is compared with the energy prices at the EEX:

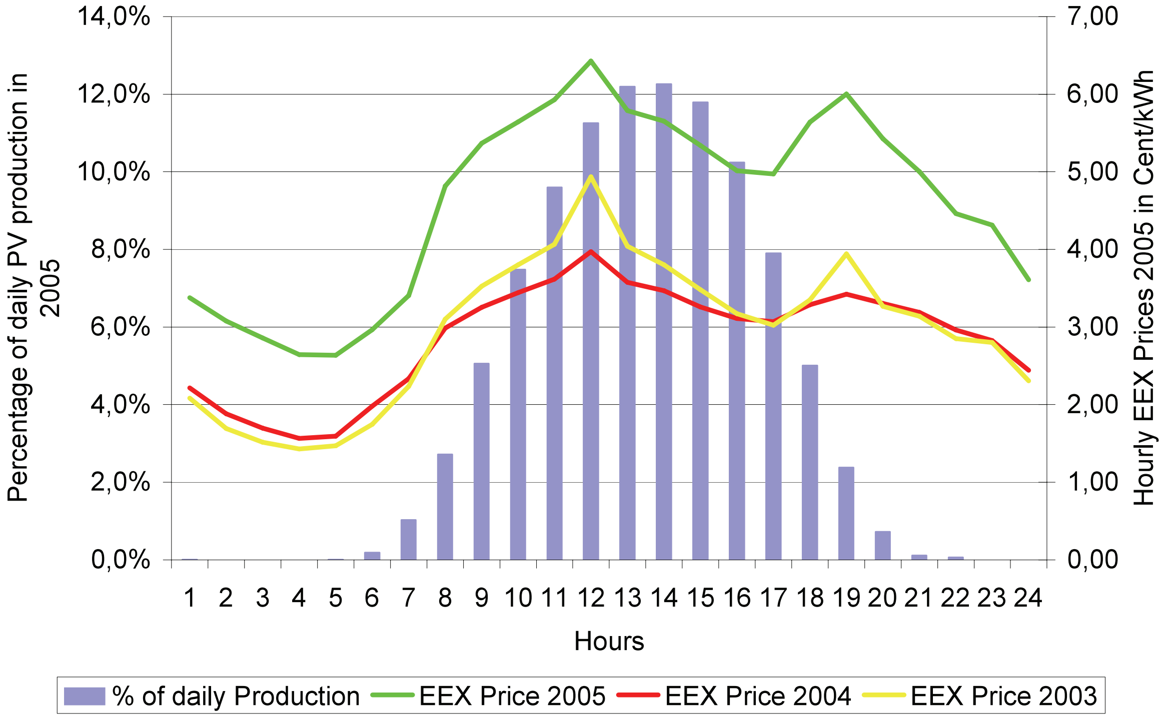

Figure 4-9: Daily distribution of PV power production compared with EEX prices

While the peak of PV power production is between 12 p.m. and 2 p.m., at the EEX two peaks of energy prices occurred, the first between 11-12 a.m. and the second 6-7 p.m.. In the graph the values for the 2004 and 2003 are also given and it is visible that the EEX peaks occurred at the same hours, even though in 2004 it was less extreme. A correlation analysis was also done for the daytime 6 a.m. to 20 p.m., where the PV energy production is higher than 0,5% of all day production (as night hours are not really relevant for PV). The correlation coefficient decreases from 0,569 in 2003, to 0,545 in 2004, to 0,476 in 2005.[49] This means that the power consumption profile (which is expressed in the price profile of the EEX) has somehow changed which is not in favour of the PV production profile. It is hard to say which reasons are responsible for that, if it is a general tendency of changing habits of energy consumption, etc.. in sunnier regions than Germany there should be a better correlation between PV energy production and electricity prices.

4.3.4 From the Value of PV to the PV Break-even Price

As the analysis before showed, the value of PV at the EEX in 2005 was 5,34 Cent/kWh, which is a little bit below the peak load price of 2005. The result also was that the monthly value of PV correlates in normal situations nearly perfectly with the monthly peak load price. In section 4.3.1.1 it could be seen that electricity prices increased a lot in 2004 and 2005, hence the question is whether the value of 2005 can be used as origin for our break-even analysis or if the lower values from the former years should be selected because 2005 was a year with abnormal high prices.

Apart from the first months of 2006, which continued with very high prices for both base load and peak load, the Futures of section 4.3.1.3 can give an idea of what the market participants are thinking about in terms of long term price developments. With Futures traded at about 6 Cent/kWh for base load and 8 Cent/kWh for peak load it is obvious that the market expects strong increasing energy prices compared to 2005. A return to times where peak load prices were under 5 Cents/kWh seems therefore very improbable. On the contrary, as the Future market signalises constantly high peak load prices, it is very probable that the value of PV will be in the region of at least 7 Cent/kWh from 2006/2007 on. This certainly will happen if climate policy continues the process of including external cost through the use of a shortage of CO_2 allowances. This will be the key determinant for the electricity prices.

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[49] In this case energy earnings of 2005 are compared with energy prices of other years as well. Systematically this is not totally correct, but because the deviation of hourly energy production should be very low in different years, the possible error is not relevant.

Therefore for the break-even analysis in this work two values will be used: One for a scenario with a low value of PV of 5,3 Cent/kWh and another with a higher assumption for the value of PV of 7 Cent/kWh (see section 4.4.2.2).

In some publications other factors are mentioned which could influence the break-even price and might make an adaptation of the break-even price necessary.

Avoided network access costs:
PV energy is a decentralised technology and a big part of the production takes place very close to the consumers (e.g. roof tops of houses or factories). This saves cost for electricity transmission. The saved costs are estimated between 0,24 and 1 Cent/kWh [BMU 2005a];[Krewitt et al. 2005a]. Because these costs are difficult to estimate and in some cases also extra costs for network access extensions for PV may arise in this break-even analysis they are not added to the value of PV.

External costs of other energy resources:
Sometimes a surcharge on the break-even prices is added because of the external costs of example fossil energy production [BMU 2005a]. While this proceeding seemed to be adequate before the introduction of CO_2 allowances now it includes the risk of a double punishment of fossil energy alternatives. As described above it can be shown, that there is a high correlation between CO_2 allowances and electricity prices. Therefore in this work no more external costs are added because of the danger of double counting external cost effects.

4.4 Calculating the Learning Investments – The Cost of PV Competitiveness

In this section the break-even analysis is presented. First the break-even model is described with the definition of the important variables. Because there are a lot of different possibilities that influence the results of the break-even analysis, the assumptions for the different scenarios are explained in detail in the second subsection. In the two following subsections the learning investments based on kWh break-even prices are analysed from a general global view on the one hand and on the German national economics view on the other.

4.4.1 The Break-even Model

During this work a break-even model was created which allows the simulation of different scenarios for the future development of PV. Compared to other studies this model has certain advantages:

Aggregation level (global and local):
The model can analyse the development of the global and the local (in this case the German) PV market separately and incorporates interrelations between the global and the local market. Some variables must therefore be defined twice; for the global and the local version.

Changing break-even prices:
The model can simulate changing break-even prices, even with different rates for global and local prices changes. Using increasing break-even prices makes it necessary to pay attention to the growth rates (see section 4.4.2.3).

Including soft factor development:
As seen in the former chapter it is important to include the change of the soft factors in an experience curve analysis. Therefore the model allows different variables for soft factor changes to be defined.

Based on kWh prices:
The break-even prices in this model are included as kWh prices of alternative energy production at first. Then the model calculates fictive PV installation prices (in €/Wp), which would be necessary to reach the given kWh break-even prices including the corresponding soft factors. The differences between the real and the fictive installation prices are the learning investments. This is done for each year separately to incorporate the change of the soft factors depending on the cumulative capacities of the regarded year (see section 4.4.1.3 for details).

Discounting of future values:
The possibility to include discount rates enables a better simulation of the financial relevance of future learning investments and gains of PV. From the point of view of economic science this is absolutely necessary for the correct evaluation of future cash flows (see section 4.4.2.4)

Win point calculation:
The model calculates the break-even year as well as the year when discounted learning investments become negative and therefore when win point is reached. This is a very interesting piece of information to evaluate scenarios not only with the necessary learning investments, but also with the time to return profits from the introduction of PV.

4.4.1.1 Definition of Variables

In this subsection follows a list of the variables used in the model. Because the model does the calculation for a global as well as for a local scenario, some variables must be defined separately.

General important variables:

Rate_PV_Install	progress ratio of PV installation price
BEP_scenario$_{global}$	scenario for the global break-even price
BEP_scenario$_{local}$	scenario for the local break-even price
Growth_Scenario$_{global}$	scenario for PV growth global
Growth_Scenario$_{local}$	scenario for PV growth local
Discount_Rate_Scenario	scenario for discounting future cash flows

General start variables:

t_0	start year
Cum_Cap$_{0,\ global}$	global cumulative installed capacities in start year
Cum_Cap$_{0,\ local}$	local cumulative installed capacities in start year
Annual_Market$_{0,\ global}$	global annual PV market in start year
Annual_Market$_{0,\ local}$	local annual PV market in start year
Install_Price$_0$	global and local installation price of a Wp PV

Soft factor start variables:

n_0	lifetime of the PV system in start year
n_max$_{global}$ / n_max$_{local}$	maximum lifetime for a future PV system
PR0$_{0,\ global}$ / PR0$_{0,\ local}$	performance ratio in start year
deg$_0$	degradation of energy earnings
c_v	yearly variable cost factor of Install_Price
inf	yearly inflation
i_{global} / i_{local}	low-risk interest rate
$r_{0,\ global}$ / $r_{0,\ local}$	interest rate for specific risk of the investment
H_{global} / H_{local}	yearly total of global irradiation
G	Irradiance at Standard Test Conditions

Soft factor progress ratio variables:

Rate_n	progress ratio of the lifetime of a PV system
Rate_PR0$_{local}$ / Rate_PR0$_{global}$	progress ratio of performances ratio
Rate_deg	progress ratio of degradation
Rate_r$_{global}$ / Rate_r$_{local}$	progress ratio of specific risk interest rate

4.4.1.2 Default Value of Variables

Although the break-even model includes many variables for simulating different scenarios normally only a few variables will be changed and the results compared. Therefore in the following the default values are given, which are used when there is nothing different mentioned in the regarded scenario. In particular the soft factor values were received from the experience curve analysis of chapter 3.

General important default values:
Rate_PV_Install = 0,8
$\text{BEP\_scenario}_{\text{global}}$ = 1
$\text{BEP\_scenario}_{\text{local}}$ = 1
$\text{Growth\_Scenario}_{\text{global}}$ = 1
$\text{Growth\_Scenario}_{\text{local}}$ = 1
Discount_Rate_Scenario = 1

General start default values:
t_0 = 2005
$\text{Cum\_Cap}_{0,\text{ global}}$ = 6,056 GW
$\text{Cum\_Cap}_{0,\text{ local}}$ = 1,39 GW
$\text{Annual\_Market}_{0,\text{ global}}$ = 1,727GW
$\text{Annual\_Market}_{0,\text{ local}}$ = 0,6 GW
Install_Price_0 = 4,72 $€_{2005}$/Wp

Soft factor start default values:
n_0 = 25 years
$\text{n\_max}_{\text{global}}$ / $\text{n\_max}_{\text{local}}$ = 50 years
$\text{PR0}_{0,\text{ global}}$ / $\text{PR0}_{0,\text{ local}}$ = 75%
deg_0 = 1%
c_v = 1,5%
inf = 2%
i_{global} / i_{local} = 6%
$r_{0,\text{ global}}$ / $r_{0,\text{ local}}$ = 3%
H_{global} = 1700 kWh/qm/yr
H_{local} = 1150 kWh/qm/yr
G = 1,0 kW/qm

Soft factor progress ratio default values:
Rate_n = 1,144

Rate_PR0$_{\text{local}}$ / Rate_PR0$_{\text{global}}$ = 1,017
Rate_deg = 0,812
Rate_r$_{\text{global}}$ / Rate_r$_{\text{local}}$ = 0,876

4.4.1.3 The Model in Detail

The break-even model simulates the different development possibilities of PV in the future. It can answer interesting questions such as: When does the price of a kWh PV become competitive (break-even point)? What learning investments are necessary? When does the economy profit from the introduction of PV in the electricity mix (win point)? Etc..

For every future year in the time horizon the following variables are calculated:
Annual_Market$_t$ = Annual_Market$_{t-1}$ * Growth_Rate$_t$
Cum_Cap$_t$ = Cum_Cap$_{t-1}$ + Annual_Market$_t$
Install_Price$_t$ = Install_Price$_0$ *((Cum_Cap$_t$ / Cum_Cap$_0$)^ (LOG(Rate_PV_Install) / LOG(2)))
BEP$_t$ = BEP$_0$ * (1 + BEP_change)^(t-t$_0$)

Also the soft factor values (n$_t$, k$_t$, PR0$_t$, deg$_t$) for each year are calculated similarly to the Install_Price$_t$, riding down the experience curve. With these variables the future fictive installation costs can be calculated. This is done to obtain the fictive Wp installation price, which would be necessary to achieve a PV kWh price equal to the break-even price of the year t including the valid soft factors of the specified year.

Fictive installation cost in year t: $$C_t = \frac{BEP_t \times H / G * PR0_t \times \sum_{s=1}^{n_t} \frac{(1-deg_t)^{s-1}}{(1+k_t)^s}}{(1 + c_v \times \sum_{s=1}^{n_t} \frac{(1+inf)^{s-1}}{(1+k_t)^s})}$$

With these two variables for each year the annual learning investment can be calculated as the difference between the real install price and the fictive install price multiplied with the volume of the annual market:
Annual_Learning$_t$ = Annual_Market$_t$ * (Install_Price$_t$ - C$_t$)

What follows is the annual discounted learning and the cumulative discounted learning costs for each year:[50]

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[50] Disc_Rate$_t$ depends upon the discount scenario used, see section 4.4.2.4

$\text{Annual\_Disc\_Learning}_t = \text{Annual\_Learning}_t * (1+\text{Disc\_Rate}_t)\text{^}-(t-t_0)$
$\text{Cum\_Disc\_Learning}_t = \text{Cum\_Disc\_Learning}_{t-1} + \text{Annual\_Disc\_Learning}_{t-1}$

The year t, when the Annual_Learning_t becomes zero or negative for the first time, is the break-even year, where PV reaches competitiveness. The cumulative discounted learning costs reach there maximum in this year and start decreasing again. In the year t, when $\text{Global\_Disc\_Learning}_t$ becomes zero or negative for the first time, the economy has a net-profit from the introduction of PV in the energy mix.

Apart from the above mentioned principal structure of the model, it can also calculate a global and a local scenario at the same time. Whereas the global scenario is completely independent from the local scenario, the local scenario depends on some factors of the global scenario (for example the growth rate).

4.4.2 General Assumptions and Definitions of the Scenarios

After presenting the principal structure and variables of the model in this section a closer look at the different possible scenarios is taken. The cost of reaching the competitiveness of PV will mainly be influenced by the development of the break-even price (the development of electricity costs), the progress ratio as a parameter for the learning velocity of PV, the growth rates of PV and certainly the discount rate. For this reason each of these points will be discussed in the following subsections.

4.4.2.1 Progress ratio of the PV Installation Price

The progress ratio of PV was extensively discussed in the former chapter. For the break-even analysis assumptions must be made for future progress ratios. This is extremely difficult and small differences in the assumptions lead to quite big differences in the results.

Constant or increasing progress ratios?
In some publications e.g. [Krewitt et al. 2005a] increasing progress ratios are used. The authors justify this with the observation, that mature technologies do not maintain the low progress ratio of the early years, however the authors do not quote a source for this observation. In this work this hypothesis can not be confirmed and constant progress ratios are assumed for the following reasons:

- PV is a high technology product and theoretical physical limits are far away, so there are innumerable possibilities for cost reductions

- PV is still at the very, very beginning of its commercial use. Even if the progress ratio might increase, this should not happen in the next 50 years because of the early stage of PV technology development.
- If using increasing progress ratios, they must be related to the cumulative capacities and not to years (as it was done in [Krewitt et al. 2005a]), because there is no dependency on years. There are no hints as to how a dependency on cumulative capacities could be reasonably modelled without including a large, unnecessary uncertainty.

Values of the progress ratios:
As shown in section 3.5.2.4 the extrapolation of kWh experience curves could be made in two different ways, using all input factors and calculating the new kWh price each time, or using the kWh progress ratio. Although the first method is more complicated it is used here for the break-even analysis, because every other soft factor change can also be examined separately. Therefore the progress ratio of PV system prices must be defined here, not the progress ratio of the PV kWh price. The PV system progress ratio, the “Rate_PV_Install”-Variable, depends on the global cumulative production, because, beside the modules which are produced and sold globally, the inverters and BOS are becoming globally traded products. To show the big impact of the progress ratio for the break-even analysis 3 scenarios will be presented:
Scenario $PR_{0,75}$: Rate_PV_Install = 0,75
Scenario $PR_{0,8}$: Rate_PV_Install = 0,80 (default)
Scenario $PR_{0,85}$: Rate_PV_Install = 0,85

Scenario $PR_{0,85}$ must be regarded as quite improbable having the experience curve results from the former chapter of this work in mind. The progress ratio for PV systems of 0,8 is selected as the default scenario and the scenario $PR_{0,75}$ as a more optimistic variant.

4.4.2.2 Development of Electricity Costs and the Break-even Price

Above, the value of PV in the public grid was analysed. While the local market consists nearly completely of grid connected PV systems, the break-even values from the power exchange can be used without problems. On the other hand, the global market also has considerable potential for other PV systems which do not compete with the price of large energy grids but with the price of decentralised power plants in mini-grids or small island systems (1-20 MW). The break-even price will rise when including these niche-markets. This will be discussed later in more detail in the section on the niche-markets 4.5.2. For the first analysis the value of the global break-even price is assumed to also be the break-even price for grid connected PV systems. The results of this analysis can therefore be interpreted as a pessimistic limit.

Increasing break-even prices:
In section 4.3.1 the strong effect of the internalisation of external costs through CO_2 allowances could be seen. Because of this and the scarcity of fossil energy resources it is very questionable if the current electricity prices can be maintained over the next few decades. Also the Futures at the power exchanges indicate an increase. In the model therefore the possibility of increasing electricity prices is included. To simulate the different break-even prices and their development in the analysis three different scenarios will be compared:

Scenario BEP_1: BEP_scenario = 1; BEP_0 = 5,3 Cent/kWh; BEP_change = 2%/year[51]
The basis for this scenario are continuing increasing fuel prices, a strong increase in worldwide energy demand and also increasing efforts of CO_2 emission reduction. This scenario is selected as default in the model because of its high probability.

Scenario BEP_2: BEP_scenario = 2; BEP_0 = 5,3 Cent/kWh; BEP_change = 1%/year
In this scenario the yearly increases of the electricity prices are smaller. This could happen if for example the energy demand is not increasing as fast as expected and if CO_2 emission reduction plays a less important role in energy policies.

Scenario BEP_3: BEP_scenario = 3; BEP_0 = 7 Cent/kWh; BEP_change = 1%/year
This scenario is aimed to reflect the expectations at the power exchanges of future electricity prices. As explained in the section above the Futures indicate a constant high price level for the years 2006 -2012. Therefore the BEP starts at a higher level in this scenario, but increases less than in BEP_1 on the long run. Should energy policy be able to continue the way of including external costs in the electricity prices, this would be the preferred scenario.

The following table gives an overview of the break-even prices of the scenarios over the next few decades:

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[51] The change is above the normal inflation because the model works with deflated values.

Year	BEP_1 in $€_{2005}$/kWh	BEP_2 in $€_{2005}$/kWh	BEP_3 in $€_{2005}$/kWh
2005	0,053	0,053	0,070
2010	0,059	0,056	0,074
2020	0,071	0,062	0,081
2030	0,087	0,068	0,090
2040	0,106	0,075	0,099
2050	0,129	0,083	0,110

Table 4-11: Future break-even prices for scenarios

4.4.2.3 Growth Rates

Early on the break-even analysis is not influenced by growth rates, because price decreases only depend on the cumulative installed capacities without reference to a time axis. In reality the situation becomes more difficult. As described above, the break-even price can not be assumed as constant and the development of the break-even price can be described best when relating it to the time axis. This implies that the development of the cumulative capacities also has to be related to the time axis, which means that assumptions of future growth are necessary.

The following table shows the different growth rates of the PV market for the years 1993 to 2004:

Year	Growth World		Growth Germany	
	Yearly	Average since 1992	Yearly	Average since 1992
1993	4%	4%	6%	6%
1994	15%	9%	6%	6%
1995	12%	10%	51%	20%
1996	14%	11%	92%	35%
1997	42%	17%	37%	35%
1998	23%	18%	-14%	25%
1999	30%	19%	30%	26%
2000	43%	22%	184%	39%
2001	36%	24%	83%	44%
2002	44%	26%	3%	39%
2003	32%	26%	130%	46%
2004	61%	29%	134%	51%

Table 4-12: Growth rates of the world and German PV market 1992-2004[52]

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[52] Source: Table 3-2

The impressive growth of the German market is obvious, although the volatility of the German yearly growth rate is very high. But also the global market has grown by more then 25% per year over the last 10 years. To simulate the effects of various future growth rates different scenarios for the global and the local market were used. In the following table the values for the global scenarios are given:

Year[53]	**2005-2010**	**2011-2020**	**2021-2030**	**2031-2040**	**2041-2050**	**2051-**
Growth$_{\textbf{global, 1}}$						
Annual_Growth_Rate$_t$	30%	20%	8%	5%	3%	0%
Annual_Market$_t$ (GW)	6	40	86	140	187	
Cum_Cap$_t$ (GW)[54]	26	226	847	1.979	3.628	
% Elec. Consumption[55]	0,2%	1,2%	3,8%	7,7%	12,8%	
Growth$_{\textbf{global, 2}}$						
Annual_Growth_Rate$_t$	30%	20%	15%	12,5%	3%	-1%
Annual_Market$_t$ (GW)	6	40	161	522	701	
Cum_Cap$_t$ (GW)	26	226	1.153	4.402	10.561	
% Elec. Consumption	0,2%	1,2%	5,2%	17,5%	38,5%	
Growth$_{\textbf{global, 3}}$						
Annual_Growth_Rate$_t$	15%	15%	15%	10%	3%	0%
Annual_Market$_t$ (GW)	3	14	57	147	198	
Cum_Cap$_t$ (GW)	19	101	428	1.425	3.166	
% Elec. Consumption	0,1%	0,5%	1,9%	5,5%	11,1%	
Growth$_{\textbf{global, 4}}$						
Annual_Growth_Rate$_t$	30%	5%	5%	5%	0%	0%
Annual_Market$_t$ (GW)	6	10	17	28	28	
Cum_Cap$_t$ (GW)	26	111	249	474	751	
% Elec. Consumption	0,2%	0,6%	1,0%	1,7%	2,4%	

Table 4-13: Scenarios for global PV growth[56]

Comments on the global growth scenarios:

Global growth scenario 1: Growth$_{global, 1}$

This scenario is very similar to the “desirable development” which is described in the

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[53] The values of the columns always represent the values of the last year of the given time period.

[54] Cum_Cap$_t$ is all PV capacities that have been installed up to the year t including installations, that might not work anymore, because their lifetime ended before the year t.

[55] Refers only to installations whose lifetime in the year t still has not terminated.

[56] The annual growth rate is valid for the whole decade, while the other variables like the annual market, the cumulative capacities and the % of electricity consumption are presented for the last year of each decade.

"Solar Energy Economy" scenario of [Krewitt et al. 2005a]. It assumes a very fast growth of the global PV market up until the year 2010 and a fast growth until the year 2020. After that the growth rates decrease considerably, but the annual market will have reached remarkable size. In the year 2050 around 13% of the global electricity production would come from PV.

Global growth scenario 2: $\text{Growth}_{\text{global, 2}}$

The difference from the $\text{Growth}_{\text{global, 1}}$ scenario is that in this scenario higher growth rates could also be achieved for the years 2020-2040. The annual growth rates are still declining and this scenario also seems quite possible, when the break-even could be reached in the early 2020ies. For the year 2050 a fairly high percentage of the global electricity mix would come from PV. This could be regarded as an obstacle for this scenario, but it's not impossible, particularly with regard to the probable replacement of other energy sources with electricity, for example in a hydrogen environment.[57]

Global growth scenario 3: $\text{Growth}_{\text{global, 3}}$

This scenario simulates a much slower growth of PV in the first and second decade, but also less decreasing growth rates. One might regard this as not very probable, but it could happen for example in a case of a strong energy policy for nuclear power. In the year 2050 the annual market would nevertheless be at about the same size as in $\text{Growth}_{\text{global, 1}}$.

Global growth scenario 4: $\text{Growth}_{\text{global, 4}}$

This is the most pessimistic scenario for PV. Although until 2010 there are high growth rates, the market stimulation efforts will be cut, because of the false assessment that the PV market will now be able to grow without support. This leads to a very strong decrease in the growth rates. The percentage of PV in the energy mix will not reach a significant level in this scenario.

Local growth scenarios:

As seen in Table 4-12 the local growth of the German market was extremely high with over 40% per year in the last 10 years. The intention of the local growth scenarios; to calculate the learning costs for the local market with more or less the

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[57] Today about a fifth of the total energy production is consumed as electricity [Eurosolar 2005]. If the percentage of electricity in the total energy production increased more strongly than in the reference case assumed, this would lead to a lower percentage of PV in the electricity mix.

same growth rates as for the global market could not be hold up, because of the limitation of surface and of the percentage of PV in the electricity power mix.[58] Even with the same annual growth rates for the local market as were used in $\text{Growth}_{\text{global, 1}}$ scenario the PV energy production would reach over 200% of the electricity mix in 2050 which is not plausible at all and also surface limits would arise. The option of including export possibilities for the local market will be discussed in section 4.5.1. The local growth scenarios are presented here:

Year	**2005-2010**	**2011-2020**	**2021-2030**	**2031-2040**	**2041-2050**	**2051-**
$\text{Growth}_{\text{local, 1}}$						
$\text{Annual\_Growth\_Rate}_t$	20%	20%	-5%	-5%	0%	0%
Annual_Market_t (GW)	1,5	9,2	5,5	3,3	3,3	
Cum_Cap_t (GW)[59]	7	53	124	166	199	
% Elec. Consumption [60]	1,0%	8,3%	19,7%	26,5%	31,7%	
$\text{Growth}_{\text{local, 2}}$						
$\text{Annual\_Growth\_Rate}_t$	0%	5%	10%	10%	5%	-2%
Annual_Market_t (GW)	0,6	1,0	2,5	6,6	10,7	
Cum_Cap_t (GW)	4	12	29	74	161	
% Elec. Consumption	0,6%	1,8%	4,5%	11,4%	26,0%	

Table 4-14: Scenarios for local PV growth[61]

Comments on the local growth scenarios:

Local growth scenario 1: $\text{Growth}_{\text{local, 1}}$

This scenario represents a very strong German support for the global PV growth. The EEG would be maintained with attractive conditions so that many investors would use the available surfaces, which results in continuing fast growth of the local installations. After 2020 the annual German market would slowly begin to decrease because of saturation effects and stronger export orientation of the German PV industry.

Local growth scenario 2: $\text{Growth}_{\text{local, 2}}$

This scenario represents the opposite development, first low growth rates, later

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[58] See the following passages for details about surface and power mix estimations.

[59] Cum_Cap_t is all installed PV capacities up to the year t including installations that might not work anymore because of the ended lifetime.

[60] Refers only to installations whose lifetime in the year t has still not terminated.

[61] The annual growth rate is valid for all the decade, while the other variables like the annual market, the cumulative capacities and the % of electricity consumption are presented for the last year of each decade.

higher ones. The PV market in Germany would not increase a lot in the next 10 years, but then moderate growth rates could be achieved. This situation could happen, when the EEG is turned unattractive in the short term and the German market is only able to recover from this when PV on the global level reaches break-even.

Limits for PV growth:
Although the raw materials for PV are widely available and the growth of the market depends only on the velocity of the extension of the production possibilities, on a long term view there might be limits because of surface usage (especially for Germany) and the percentage of PV use in the power generation mix. Both limits will be briefly discussed here:

Power generation mix limits for the growth scenarios:
One limit for the growth scenarios could be the percentage of PV in the power generation mix. There exists many different scenarios about future electricity consumption.[62] For better comparison reasons in this work as in many other studies the reference scenario of IEA is used for global electrical power prognosis and the EWI/Prognos study for German prognosis.

Year	Global (IEA Energy Outlook) in TWh	Germany EWI/Prognos in TWh
2003	16.200	602
2010	19.973	612
2020	25.818	589
2030	30.855	583
2040	36.346	574
2050	40.500	564

Table 4-15: Prognosis for future electricity consumption[63]

A very high percentage, this means over 50%, of PV in the electricity power generation mix seems to not be very plausible. Using scenarios with a higher percentage could only be based on assumptions of a stronger electricity consumption growth or the substitution of other energy sources with PV (for example fossil fuels in the traffic sector with hydrogen produced by PV). Even with the above selected local scenarios in about 20 years it might be necessary to introduce buffering systems

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[62] for an overview see: [Krewitt et al. 2005a]

[63] Sources: [EWI/Prognos 2005];[Krewitt et al. 2005a] local values after 2020 interpolated

because PV will achieve a critical share of the total electricity generation capacity of around 120 GW.

Surface limits for the growth scenarios:
The above growth scenarios seem to be very ambitious having the present numbers in mind and are therefore raise the question of whether limits for the growth of PV from the point of view of usable surfaces exist. Assuming the use of only 2% of the global surface of the continents for PV installations and reducing this surface by the half as effective module surface returns in 1.445.000 km^2. This corresponds to 144.500 GW when assuming pessimistic 10m^2 for 1 kWp.[64]

For Germany the limits of the surface usage are also very high, but not negligible. If looking again at 2% land use for PV installations. An effective module surface of 3.570 km^2 corresponds to a installation capacity of 357 GW. Using a future surface use of 7m^2 for 1 kWp (instead 10m^2 for 1 kWp) the installation capacity raises to 510 GW. Using 2% of the surface for PV installations may seem a lot, but it is realistic having in mind that in Germany more than 6% of the surface is edificial and constructed surface and without counting facades and traffic routes.[65] Other publications like [BMU 2004] or [Krewitt et al. 2005a] estimate the surface limits for the growth of PV more pessimistically (29.000 GW worldwide, 165 GW o 105 GW for Germany). But even these values are very high compared to the limits when looking at the power generation mix.

It can be concluded that PV growth limits both worldwide and Germany wide will occur first due to the high share of PV in the energy mix and not due to surface restrictions.

4.4.2.4 Discount Rates

One of the most important variables which determine the results of a break-even analysis (or every other long term study) is the discount rate. In many studies e.g. [Krewitt et al. 2005a];[BMU 2005a] future cash flows are not discounted and the topic is not discussed. As mentioned before this is one of most important criticisms of these studies, because the future gains of PV will be overrated. Not discounting future cash flows is the same as using a discount rate of 0%. In other words, it is

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[64] Global surface of continents: 144,5 Mio km^2, Surface of Germany: 357.000 km^2 (Source: http://de.wikipedia.org)

[65] Source: http://www.destatis.de/basis/d/umw/ugrtab7.php

assumed that every future cash flow has the same value as today, even if it occurs in 20, 50 or 500 years time. It is obvious that this is not the case and society gives a lower value on a future gain or loss than on the same gain or loss occurring now.

For this reason discounting future cash-flows is universal in an economic analysis, but which discount rate to use is always controversially discussed. While the imputed interest, (see 3.3.7 and 3.4.2.8) which is used for discounting cash flows of a certain project, depends on the risk of the regarded project, the "social discount rate" for long term scenarios depends on the value which society gives to future cash flows. To show the dramatic impact on the break-even analysis a short example is given: The gain of 1 Euro in 50 years time discounted with 1% still accounts for 0,608 Euros today, while discounted with 6% only accounts for 0,054 Euros. The difference of the value is more than 10 times.

The break-even analysis is obviously a long term study where for many years learning costs have to be invested and the future gains of riding down the experience curves are big, but also far in the future (between 20 and 50 years, depending on the other variables of the break-even analysis). This means that using a high discount rate would reduce the economic profit of PV a lot.

The concept of the social discount rate:
The social discount rate is the discount rate employed by the government in evaluating projects and policies. There were many different approaches for the social discount rate, but now a consensus has been reached that the social discount rate should be based on the "social rate of time preference" [Guo et al. 2005]. The social rate of time preference is usually presented in the following equation, called the Ramsey equation [Ramsey 1928]:
$s = \rho + \mu^* g$

It is the sum of two factors: ρ called the "pure" rate of time preference, expressing people's impatience, and the product of g, the growth rate of future per capita consumption, multiplied with the factor μ. This factor is the income elasticity of the marginal utility. In other words the percentage change in well-being derived from the percentage change in consumption (or income).

In the year 2003 a plausible "social rate of time preference" for the UK was estimated at 3,5% by [H.M. Treasury 2003] for the use in official government long term projects, studies and scenarios. The variables were estimated ρ = 1,5%, μ = 1 and g = 2%. These values of the variables are adequate for Germany as well and therefore a social discount rate of 3,5% is also regarded as appropriate for the break-even analysis in this work and defined a scenario $Disc_1$ (Discount_Rate_Scenario = 1).

Declining discount rates:
In recent years a new concept for discount rates emerged, the declining discount rates. [Weitzmann 1998] showed that future discount rates are uncertain and therefore different discount rates must be used with their corresponding probabilities. This returns a “certainty-equivalent discount rate” at each point of the time horizon. It can be shown that this “certainty-equivalent discount rate” is declining over timer and converge to the lowest possible discount rate used. In another publication [Weitzmann 2001] surveyed more than 2000 economists and concluded that the underlying distribution of discount rates follows a Gamma distribution. He also proposes a step decline schedule to approximate the gamma discounting. The following table summarizes these results.

Years	Discount Rate
1-5	4%
6-25	3%
26-75	2%
76-300	1%
301+	0%

Table 4-16: Step decline schedule to approximate gamma discounting[66]

Other different models have been published which deal with the uncertainty of discount rates and include very interesting approaches (see [Groom et al. 2005] and [Groom et al. 2003] for a good overview). But the theory in this is still very new and it is still open with regard to which approach (some of them get quite complex very quickly and depend on a lot of further factors) will be a new consensus for the use in long term scenarios.

It is obvious that declining discount rates will add more value to the future gains of PV growth. Recent advances in economic theory may have important implications for long term scenarios. Therefore in this work a second scenario $Disc_2$ is also used with the Weitzmann step decline schedule for discount rates (Discount_Rate_Scenario = 2).

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[66] Source: [Weitzmann 2001]

4.4.3 Learning Costs based on KWh prices

After describing the model and the assumptions the results of the break-even model are presented in this subsection for the global view and in the following subsection for the local German view. At first the global default scenario is presented here in detail, then combinations of the different scenarios are given. The global default scenario consists of the combination of the $Disc_1/PR_{0,8}/BEP_1/Growth_{global,\ 1}$ scenarios.

Results Global:	**Start**	**Break-even**	**Win Point**	**Year 2050**
Year	2005	2025	2037	2050
Price of PV in $€_{2005}$/Wp	4,72	1,16	0,79	0,60
kWh-Price of PV in $€_{2005}$/kWh	0,478	0,0799	0,0511	0,0376
BEP_t in $€_{2005}$/kWh	0,053	0,0788	0,0999	0,1292
Fictive Installation Cost C_t in $€_{2005}$/Wp	0,52	1,14	1,54	2,07
Cumulative Capacity in GW	6,1	478	1580	3628
Yearly Market in GW/year	1,7	58	121	188
Disc. Learning Cost in Billion $€_{2005}$[67]	0	204	13	-591
Share of PV of Electricity Production	0,04%	2,3%	6,5%	12,8%

Table 4-17: Results for $Disc_1/PR_{0,8}/BEP_1/Growth_{global,\ 1}$ scenario

With decreasing PV prices and increasing energy prices the break-even is reached in the year 2025, where the PV will cost about 0,08 $€_{2005}$/kWh. The cumulative learning investment will have reached its maximum and start to decrease. It will need until the year 2037 for the win point to be reached, but in the year 2050 a profit of nearly 600 billion $Euro_{2005}$ will be made, which is about 3 times as high as the maximum learning investments.

Changing the discount scenario and using the Weitzmann step decline schedule for discount rates (scenario $Disc_2$) even improves the result reasonably. The win point is reached two years earlier and in 2050 the benefits of introducing PV will have exceed 1100 billion $Euro_{2005}$.

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[67] For the win point the value should be zero in theory, but the deviation originates from the calculation on yearly basis. In the following year after the win point the value is always negative.

Results Global:	**Start**	**Break-even**	**Win Point**	**Year 2050**
Year	2005	2025	2035	2050
Price of PV in $€_{2005}$/Wp	4,72	1,16	0,83	0,60
kWh-Price of PV in $€_{2005}$/kWh	0,478	0,0799	0,0542	0,0376
BEP_t in $€_{2005}$/kWh	0,053	0,0788	0,0960	0,1292
Fictive Installation Cost C_t in $€_{2005}$/Wp	0,52	1,14	1,47	2,07
Cumulative Capacity in GW	6,1	478	1345	3628
Yearly Market in GW/year	1,7	58	109	188
Disc. Learning Cost in Billion $€_{2005}$	0	213	21	-1149
Share of PV of Electricity Production	0,04%	2,3%	5,7%	12,8%

Table 4-18: Results for $Disc_2/PR_{0,8}/BEP_1/Growth_{global,\ 1}$ scenario

The difference of these two scenarios should emphasize again the importance of the right social discounting. Using no discount rates (which means a discount rate of zero) would return even higher profits for the introduction of PV, but it is in contradiction to economic science.

Combination of different scenarios:

The effects of the different scenarios are clarified through combining the scenarios. The following table therefore gives an overview of the combination of the scenarios.

			Break-even			Win Point		Year 2050	
			Year	Discounted Learning Inv. in bn €$_{2005}$	PV Price in €$_{2005}$/kWh	Year	PV Price in €$_{2005}$/kWh	Discounted Learning Inv. in bn €$_{2005}$	PV Price in €$_{2005}$/kWh
PR$_{0,75}$	BEP$_1$	Growth$_{\text{global}, 1}$	2020	117	0,076	2029	0,043	-1012	0,021
		Growth$_{\text{global}, 2}$	2020	117	0,076	2027	0,044	-4012	0,013
		Growth$_{\text{global}, 3}$	2025	103	0,079	2034	0,044	-850	0,022
		Growth$_{\text{global}, 4}$	2026	109	0,084	2049	0,044	-6	0,043
	BEP$_2$	Growth$_{\text{global}, 1}$	2022	134	0,065	2033	0,036	-528	0,021
		Growth$_{\text{global}, 2}$	2022	134	0,064	2030	0,035	-2456	0,013
		Growth$_{\text{global}, 3}$	2027	120	0,069	2038	0,035	-414	0,022
		Growth$_{\text{global}, 4}$	2031	125	0,070	>2060		80	0,043
	BEP$_3$	Growth$_{\text{global}, 1}$	2019	95	0,083	2027	0,048	-960	0,021
		Growth$_{\text{global}, 2}$	2019	95	0,083	2026	0,047	-3679	0,013
		Growth$_{\text{global}, 3}$	2024	88	0,084	2033	0,047	-766	0,022
		Growth$_{\text{global}, 4}$	2025	93	0,087	2048	0,045	-8	0,043
PR$_{0,8}$	BEP$_1$	Growth$_{\text{global}, 1}$	2025	204	0,080	2037	0,051	-591	0,038
		Growth$_{\text{global}, 2}$	2024	205	0,082	2032	0,052	-3115	0,025
		Growth$_{\text{global}, 3}$	2029	167	0,088	2039	0,055	-511	0,040
		Growth$_{\text{global}, 4}$	2033	167	0,095	>2060		110	0,067
	BEP$_2$	Growth$_{\text{global}, 1}$	2028	251	0,070	2046	0,041	-106	0,038
		Growth$_{\text{global}, 2}$	2027	252	0,068	2036	0,042	-1559	0,025
		Growth$_{\text{global}, 3}$	2033	211	0,072	2047	0,043	-75	0,040
		Growth$_{\text{global}, 4}$	2042	203	0,077	>2060		197	0,067
	BEP$_3$	Growth$_{\text{global}, 1}$	2023	168	0,089	2035	0,054	-538	0,038
		Growth$_{\text{global}, 2}$	2023	168	0,087	2031	0,054	-2782	0,025
		Growth$_{\text{global}, 3}$	2028	146	0,093	2039	0,055	-427	0,040
		Growth$_{\text{global}, 4}$	2033	149	0,095	>2060		108	0,067
PR$_{0,85}$	BEP$_1$	Growth$_{\text{global}, 1}$	2032	413	0,094	2050	0,066	32	0,066
		Growth$_{\text{global}, 2}$	2030	428	0,091	2039	0,065	-1661	0,049
		Growth$_{\text{global}, 3}$	2035	312	0,101	2049	0,070	-15	0,068
		Growth$_{\text{global}, 4}$	2042	271	0,114	>2060		261	0,103
	BEP$_2$	Growth$_{\text{global}, 1}$	2041	572	0,076	>2060		517	0,066
		Growth$_{\text{global}, 2}$	2035	610	0,075	2048	0,051	-105	0,049
		Growth$_{\text{global}, 3}$	2043	459	0,079	>2060		421	0,068
		Growth$_{\text{global}, 4}$	2061	355	0,093	>2060		347	0,103
	BEP$_3$	Growth$_{\text{global}, 1}$	2032	361	0,094	2052	0,064	84	0,066
		Growth$_{\text{global}, 2}$	2030	368	0,091	2039	0,065	-1328	0,049
		Growth$_{\text{global}, 3}$	2036	291	0,097	2052	0,066	69	0,068
		Growth$_{\text{global}, 4}$	2046	261	0,108	>2060		259	0,103

Table 4-19: Results for the Disc$_1$/PR$_{0,75\text{-}0,85}$/BEP$_{1\text{-}3}$/Growth$_{\text{global}, 1\text{-}4}$ scenarios[68]

Logically the gains of introducing PV are increased significantly with falling progress ratios. With a high progress ratio of 0,85 the win point could not be reached until 2050 for more than half of the scenarios. Only with a very fast and long continuing

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[68] Values for win points beyond 2060 can not be presented, because the growth scenarios are only applicable until the year 2060.

growth of PV ($\mathrm{Growth}_{\mathrm{global},\,2}$) would high economic profits be possible. The discounted learning investments are halved every time the progress ratio decreases 5%.

For the extreme growth scenario $\mathrm{Growth}_{\mathrm{global},\,2}$ the break-even point (win point) will always be reached before 2035 (2048) even assuming very unfavourable developments of progress ratio and break-even prices. The very slow growth scenario $\mathrm{Growth}_{\mathrm{global},\,4}$ will never reach the win point before 2048 and for the majority of the scenarios no win point could be calculated because the time frame is exceeded. This means that in the $\mathrm{Growth}_{\mathrm{global},\,4}$ scenario, where the installed capacities are raised from about 6 GW to more than 600 GW, the probability of regaining the learning costs is very limited.

For all break-even scenarios $\mathrm{BEP}_{1\text{-}3}$ the win point is always reached before 2050 if a progress ratio of 0,8 or better is achieved and the slow $\mathrm{Growth}_{\mathrm{global},\,4}$ scenario is excluded. This signifies that if the growth of photovoltaic is not very slow and the learning rate is maintained at a moderate level it will be economically worth introducing PV even without knowing the exact price development of the break-even prices. Even slowly ascending break-even prices will not prevent the economic advantage of the introduction of PV in the global electricity mix.

In the next table the same scenarios are presented with the Weitzmann step decline schedule for discount rates (scenario Disc_2).

			Break-even			Win Point		Year 2050	
			Year	Discounted Learning Inv. in bn €$_{2005}$	PV Price in €$_{2005}$/kWh	Year	PV Price in €$_{2005}$/kWh	Discounted Learning Inv. in bn €$_{2005}$	PV Price in €$_{2005}$/kWh
$PR_{0,75}$	BEP_1	$\text{Growth}_{\text{global, 1}}$	2020	120	0,076	2029	0,043	-1756	0,021
		$\text{Growth}_{\text{global, 2}}$	2020	120	0,076	2027	0,044	-6935	0,013
		$\text{Growth}_{\text{global, 3}}$	2025	107	0,079	2032	0,049	-1539	0,022
		$\text{Growth}_{\text{global, 4}}$	2026	112	0,084	2043	0,050	-86	0,043
	BEP_2	$\text{Growth}_{\text{global, 1}}$	2022	139	0,065	2032	0,037	-966	0,021
		$\text{Growth}_{\text{global, 2}}$	2022	138	0,064	2029	0,038	-4289	0,013
		$\text{Growth}_{\text{global, 3}}$	2027	125	0,069	2036	0,039	-803	0,022
		$\text{Growth}_{\text{global, 4}}$	2031	129	0,070	2057	0,039	51	0,043
	BEP_3	$\text{Growth}_{\text{global, 1}}$	2019	98	0,083	2027	0,048	-1625	0,021
		$\text{Growth}_{\text{global, 2}}$	2019	98	0,083	2026	0,047	-6292	0,013
		$\text{Growth}_{\text{global, 3}}$	2024	91	0,084	2032	0,049	-1371	0,022
		$\text{Growth}_{\text{global, 4}}$	2025	95	0,087	2043	0,050	-76	0,043
$PR_{0,8}$	BEP_1	$\text{Growth}_{\text{global, 1}}$	2025	213	0,080	2035	0,054	-1149	0,038
		$\text{Growth}_{\text{global, 2}}$	2024	213	0,082	2031	0,054	-5543	0,025
		$\text{Growth}_{\text{global, 3}}$	2029	175	0,088	2037	0,060	-1018	0,040
		$\text{Growth}_{\text{global, 4}}$	2033	176	0,095	2056	0,063	74	0,067
	BEP_2	$\text{Growth}_{\text{global, 1}}$	2028	264	0,070	2042	0,045	-359	0,038
		$\text{Growth}_{\text{global, 2}}$	2027	265	0,068	2035	0,044	-2897	0,025
		$\text{Growth}_{\text{global, 3}}$	2033	229	0,072	2044	0,046	-282	0,040
		$\text{Growth}_{\text{global, 4}}$	2042	224	0,077	>2060		211	0,067
	BEP_3	$\text{Growth}_{\text{global, 1}}$	2023	174	0,089	2034	0,056	-1019	0,038
		$\text{Growth}_{\text{global, 2}}$	2023	174	0,087	2030	0,057	-4901	0,025
		$\text{Growth}_{\text{global, 3}}$	2028	153	0,093	2037	0,060	-850	0,040
		$\text{Growth}_{\text{global, 4}}$	2033	156	0,095	>2060		84	0,067
$PR_{0,85}$	BEP_1	$\text{Growth}_{\text{global, 1}}$	2032	444	0,094	2046	0,070	-236	0,066
		$\text{Growth}_{\text{global, 2}}$	2030	457	0,091	2038	0,067	-3246	0,049
		$\text{Growth}_{\text{global, 3}}$	2035	351	0,101	2046	0,074	-241	0,068
		$\text{Growth}_{\text{global, 4}}$	2042	304	0,114	>2060		285	0,103
	BEP_2	$\text{Growth}_{\text{global, 1}}$	2041	657	0,076	>2060		554	0,066
		$\text{Growth}_{\text{global, 2}}$	2035	691	0,075	2045	0,054	-600	0,049
		$\text{Growth}_{\text{global, 3}}$	2043	566	0,079	>2060		495	0,068
		$\text{Growth}_{\text{global, 4}}$	2061	438	0,093	>2060		422	0,103
	BEP_3	$\text{Growth}_{\text{global, 1}}$	2032	387	0,094	2047	0,069	-106	0,066
		$\text{Growth}_{\text{global, 2}}$	2030	392	0,091	2038	0,067	-2603	0,049
		$\text{Growth}_{\text{global, 3}}$	2036	328	0,097	2048	0,071	-73	0,068
		$\text{Growth}_{\text{global, 4}}$	2046	298	0,108	>2060		295	0,103

Table 4-20: Results for the $\text{Disc}_2/\text{PR}_{0,75\text{-}0,85}/\text{BEP}_{1\text{-}3}/\text{Growth}_{\text{global, 1-4}}$ scenarios

The year of break-even and the corresponding PV-price as well as the PV-price of the year 2050 are identical in both discount scenarios. The discounted learning investments until break-even are higher in Disc_2, because future cash-flows are discounted with smaller discount rates (see section 4.4.2.4 for details). On the other hand in Disc_2 the win point is reached earlier or within the same year. Also in Disc_2 the profits in the year 2050 of introducing PV are significantly higher for all scenarios which will have reached the win point before 2050.

Comparison with other studies:
It is difficult to compare the results of this break-even analysis with other studies. As a tendency it can be seen that the learning costs are lower than in other studies, mostly due to the effects of using changing break-even prices (not done in [Schaeffer et al. 2004a]) and discounting of future cash flows (not done in [Schaeffer et al. 2004a];[Krewitt et al. 2005a]). This last reason is also responsible for why the win point is generally reached later than in other papers.

4.4.4 Learning Costs from the National Economics View of Germany

Since the year 2000, Germany has been one of the most important markets worldwide for PV. Due to the German Renewable Energy Law (EEG) the demand for PV has increased strongly. For this reason at the moment Germany is paying a reasonable part of the global learning investments.[69] What are the possibilities for Germany to regain its investments? The following table includes the local scenarios for Germany while assuming the default global growth scenario Growth$_{global, 1}$.

			Break-even			**Win Point**		**Year 2050**	
			Year	**Discounted Learning Inv. in bn €$_{2005}$**	**PV Price in €$_{2005}$/kWh**	**Year**	**PV Price in €$_{2005}$/kWh**	**Discounted Learning Inv. in bn €$_{2005}$**	**PV Price in €$_{2005}$/kWh**
PR$_{0,75}$	BEP$_1$	Growth$_{local, 1}$	2025	42	0,079	>2060		26	0,033
		Growth$_{local, 2}$	2026	14	0,081	2044	0,039	-11	0,033
	BEP$_2$	Growth$_{local, 1}$	2028	47	0,067	>2060		40	0,033
		Growth$_{local, 2}$	2029	15	0,069	2052	0,031	3	0,033
	BEP$_3$	Growth$_{local, 1}$	2023	37	0,089	>2060		22	0,033
		Growth$_{local, 2}$	2025	13	0,086	2044	0,039	-8	0,033
PR$_{0,8}$	BEP$_1$	Growth$_{local, 1}$	2032	69	0,091	>2060		62	0,059
		Growth$_{local, 2}$	2033	20	0,093	2054	0,055	7	0,060
	BEP$_2$	Growth$_{local, 1}$	2038	77	0,076	>2060		76	0,059
		Growth$_{local, 2}$	2040	23	0,075	>2060		20	0,060
	BEP$_3$	Growth$_{local, 1}$	2031	62	0,094	>2060		57	0,059
		Growth$_{local, 2}$	2033	19	0,093	2058	0,052	9	0,060
PR$_{0,85}$	BEP$_1$	Growth$_{local, 1}$	2043	111	0,114	>2060		110	0,103
		Growth$_{local, 2}$	2044	34	0,115	>2060		32	0,104
	BEP$_2$	Growth$_{local, 1}$	2060	125	0,093	>2060		124	0,103
		Growth$_{local, 2}$	2060	48	0,092	>2060		46	0,104
	BEP$_3$	Growth$_{local, 1}$	2047	106	0,107	>2060		106	0,103
		Growth$_{local, 2}$	2048	34	0,107	>2060		34	0,104

Table 4-21: Results for the Disc$_1$/PR$_{0,75-0,85}$/BEP$_{1-3}$/ Growth$_{local, 1-2/}$Growth$_{global, 1}$ scenarios

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[69] In the case of Germany the learning investments of the local scenarios can not be related to the global scenarios because they use different variables for the yearly total of global irradiation.

As it can be seen the possibilities are very limited. Germany could never reach the win point before 2060 if continuing with the fast introduction of PV as described in the Growth$_{\text{local, 1}}$ scenario. Because of the limitations of growth mentioned in section 4.4.2.3 there would be no possibility to grow and profit in the years after break-even, when PV is cheaper, in a way that learning investments could be regained. Although for example in the PR$_{0,75}$/Growth$_{\text{local, 1}}$ scenarios the break-even is reached in the years 2023-2028; quite early, the installation capacities afterwards are not sufficient. The situation changes if using the second growth scenario Growth$_{\text{local, 2}}$, which describes a slow growth in the early years and therefore more capacities are installed after break-even. Apart from the PR$_{0,8}$/BEP$_2$ scenario the win point will be reached before 2060 for the other PR$_{0,75\text{-}0,8}$/Growth$_{\text{local, 2}}$ scenarios.

Similarly to the global break-even analysis, the second discount rate scenario can also be used here, but will not change the principal result.

			Break-even			**Win Point**		**Year 2050**	
			Year	**Discounted Learning Inv. in bn €$_{2005}$**	**PV Price in €$_{2005}$/kWh**	**Year**	**PV Price in €$_{2005}$/kWh**	**Discounted Learning Inv. in bn €$_{2005}$**	**PV Price in €$_{2005}$/kWh**
PR$_{0,75}$	BEP$_1$	Growth$_{\text{local, 1}}$	2025	44	0,079	>2060		18	0,033
		Growth$_{\text{local, 2}}$	2026	14	0,081	2041	0,042	-29	0,033
	BEP$_2$	Growth$_{\text{local, 1}}$	2028	49	0,067	>2060		37	0,033
		Growth$_{\text{local, 2}}$	2029	16	0,069	2047	0,036	-6	0,033
	BEP$_3$	Growth$_{\text{local, 1}}$	2023	38	0,089	>2060		14	0,033
		Growth$_{\text{local, 2}}$	2025	13	0,086	2041	0,042	-24	0,033
PR$_{0,8}$	BEP$_1$	Growth$_{\text{local, 1}}$	2032	72	0,091	>2060		61	0,059
		Growth$_{\text{local, 2}}$	2033	21	0,093	2048	0,062	-3	0,060
	BEP$_2$	Growth$_{\text{local, 1}}$	2038	83	0,076	>2060		80	0,059
		Growth$_{\text{local, 2}}$	2040	25	0,075	>2060		20	0,060
	BEP$_3$	Growth$_{\text{local, 1}}$	2031	65	0,094	>2060		57	0,059
		Growth$_{\text{local, 2}}$	2033	19	0,093	2050	0,060	2	0,060
PR$_{0,85}$	BEP$_1$	Growth$_{\text{local, 1}}$	2043	121	0,114	>2060		120	0,103
		Growth$_{\text{local, 2}}$	2044	39	0,115	>2060		35	0,104
	BEP$_2$	Growth$_{\text{local, 1}}$	2060	140	0,093	>2060		139	0,103
		Growth$_{\text{local, 2}}$	2060	62	0,092	>2060		58	0,104
	BEP$_3$	Growth$_{\text{local, 1}}$	2047	116	0,107	>2060		116	0,103
		Growth$_{\text{local, 2}}$	2048	40	0,107	>2060		40	0,104

Table 4-22: Results for the Disc$_2$/PR$_{0,75\text{-}0,85}$/BEP$_{1\text{-}3}$/Growth$_{\text{local, 1-2}}$/Growth$_{\text{global, 1}}$ scenarios

Interpretations:

As a consequence of this analysis one could be tempted to conclude, that a strong policy support and a fast growth strategy for PV in Germany will have a negative effect on the economy and there will be accumulated learning investments that could never be regained. This would signify that it is better to cut the PV support and wait for falling PV prices to be able to use the limited growth possibilities inside Germany when prices would be at a lower level and learning costs would be smaller.

But this conclusion would disregard some important aspects and therefore would not be correct:
Global growth depends on local growths:
For every local market compared to the global market it seems better to wait with regard to growth until prices have come down. But if all local markets follow this idea, the global growth velocity of scenario $\text{Growth}_{\text{global, }1}$ would not be reached. On the contrary the PV development would more likely be as described in the scenario $\text{Growth}_{\text{global, }4}$,which would again have a backlash on the local scenarios (which means still worse consequences).

Local PV growth is influencing import quota:
If a part of the energy system is changed from fossil/nuclear technologies to PV, changes of the added value for the gross domestic product will occur. For example, for the production of a kWh of electricity in a gas steam power plant, a big part of the costs rely on the importation of gas. If PV replaces electricity from gas steam power plants the local economy benefits because a bigger part of the added value is created inside the country. A closer examination of the change of the import quota due to the replacement of other energy sources with PV will reveal further gains for the local economy, but can not be part of this work.

Export possibilities:
Not only the allocation of added value in the electricity economy is changing, also new export possibilities are arising. Having a fast growing, competitive PV industry, new markets outside the local markets can be accessed successfully. Increasing net exports directly augments the gross domestic product. This effect can be tremendous for the exporting economy and therefore is researched separately (see section 4.5.1).

4.5 Discussion of alternative Scenarios

After analysing the learning investments in general on a global and a local basis in this section two alternative scenarios are discussed. First the possibility of export for the German economy is presented and second niche-markets with higher break-even prices are included in the global analysis.

4.5.1 Including Export in Local Scenarios

In section 4.4.4 the learning costs from the national point of view of Germany were analysed. The result was that in many scenarios the invested learning costs of the German economy could not be regained and the win point would not be reached due to the limitations of PV growth in the electric power mix. The local scenarios so far disregarded a very important point: The chance of export success of a leading PV industry, which exists, if Germany continues to be one of the world's main promoters of introducing solar energy. In this section therefore the adaptation of the break-even model including possible export numbers is presented.

4.5.1.1 Evaluation of Export Success

Every economy tries to increase their exports because augmenting net exports leads to an increasing gross domestic product.[70] The emphasis lies on net exports; which are exports minus imports. If looking today at a specific industry sector and analysing the growth of its exports, it is also important to know the imports that have been made to produce the exported goods. If only counting export numbers the success would be overestimated. In an optimistic assumption one could argue that the PV industry is a high-tech industry so that most of the added value will occur in the national economy. There are no expensive raw materials necessary if all steps of the value chain including silicon waver production could be made in Germany. On the other hand generally with growing exports there are clear tendencies of increased imports which are export induced. A recent publication of the Statistisches Bundesamt analysed the numbers for the German economy in general [Statistisches Bundesamt 2004]. The result was that nearly 40% of the export value was imported before, so that when looking at a 1 Euro export value only 60 Cents were added value of the German economy and increased the gross domestic product.

In the break-even model an even more conservative assumption of only 50% added value of exports is assumed. Although it is very probable that the export induced imports for the PV sector are lower than 40%, one should have in mind that not all parts of a PV system are exported. More probable is that installation work and some parts of the BOS production will be done by the local importing economy. Therefore in the model only half of the exported PV system price is counted as added value to the gross domestic product for the German economy. This can still be regarded a conservative assumption.

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[70] The gross domestic product can be expressed: GDP = consumption + investment + government spending + (exports − imports)

4.5.1.2 Learning Costs including Export

To best measure the impact of the PV exports, the local scenarios were enhanced. The goal was to change the global and local scenarios as little as possible for better comparison of the results.

Therefore the numbers of the local growth scenarios above were not changed with regard to the PV systems installed in Germany. This means that the learning investments and the results of the local break-even analysis will be comparable and only enhanced through the gains of the export efforts. The export growth rates were obtained though the following change in the local growth scenario: The local PV industry will grow with the same growth rates as the global industry. The difference between these new local growth rates and the locally installed PV systems of the originally local scenarios is obviously the number of the exported PV systems.[71]

In the following table the numbers of the local scenario without and with export are compared.

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[71] This approach implies that in 2006 the difference between export and import is that the net export becomes positive for the first time. In 2005 and the years before Germany had net import of solar products, because of the tremendously fast increasing demand. In 2006 the production capacities of inverters, cells, and modules will be able to at least cover the German market [Kreutzmann 2006].

			Break-even without Export		**Break-even with Export**			**Win Point with Export**	**Year 2050 without Export**	**Year 2050 with Export**
			Year	**Disc. Learning Inv. in bn €$_{2005}$**	**Year**	**Disc. Learning Inv. in bn €$_{2005}$**	**Export quota**	**Year**	**Disc. Learning Inv. in bn €$_{2005}$**	**Disc. Learning Inv. in bn €$_{2005}$**
PR$_{0,75}$	BEP$_1$	Growth$_{local, 1}$	2025	42	2020	26	0,33	2030	26	-67
		Growth$_{local, 2}$	2026	14	2008	3	0,54	2012	-11	-133
	BEP$_2$	Growth$_{local, 1}$	2028	47	2021	28	0,41	2032	40	-53
		Growth$_{local, 2}$	2029	15	2008	3	0,54	2012	3	-120
	BEP$_3$	Growth$_{local, 1}$	2023	37	2020	22	0,33	2028	22	-71
		Growth$_{local, 2}$	2025	13	2008	3	0,54	2011	-8	-131
PR$_{0,8}$	BEP$_1$	Growth$_{local, 1}$	2032	69	2021	38	0,41	2032	62	-86
		Growth$_{local, 2}$	2033	20	2008	4	0,54	2012	7	-181
	BEP$_2$	Growth$_{local, 1}$	2038	77	2022	41	0,48	2034	76	-72
		Growth$_{local, 2}$	2040	23	2008	4	0,54	2012	20	-167
	BEP$_3$	Growth$_{local, 1}$	2031	62	2021	34	0,41	2031	57	-91
		Growth$_{local, 2}$	2033	19	2008	3	0,54	2011	9	-179
PR$_{0,85}$	BEP$_1$	Growth$_{local, 1}$	2043	111	2022	55	0,48	2034	110	-122
		Growth$_{local, 2}$	2044	34	2008	4	0,54	2011	32	-251
	BEP$_2$	Growth$_{local, 1}$	2060	125	2023	58	0,54	2035	124	-108
		Growth$_{local, 2}$	2060	48	2008	4	0,54	2012	46	-237
	BEP$_3$	Growth$_{local, 1}$	2047	106	2022	50	0,48	2033	106	-127
		Growth$_{local, 2}$	2048	34	2008	4	0,54	2011	34	-249

Table 4-23: Disc$_1$/PR$_{0,75-0,85}$/BEP$_{1-3}$/ Growth$_{local, 1-2}$/Growth$_{global, 1}$ with Export

As it can be seen the situation changes completely when including export possibilities in the analysis. For the fast local growth scenario Growth$_{local, 1}$ the break-even will now be reached between the years 2020 and 2023 depending on the other assumptions. While without export the win point will only be reached in very few scenarios., with Export the win point is in the years 2028-2035. Assuming the slow local growth scenario Growth$_{local, 2}$ the situation is even more comfortable. Break-even is reached in the year 2008 and the win point in the years 2011/2012. Looking at the year 2050 in any case the German economy will profit from the introduction. The fact that the slow growth scenario will return better results than the fast growth scenario does not change when including export, but the differences get smaller. The export quota in 2050 for Growth$_{local, 1}$ (Growth$_{local, 2}$) will be 95% and 84%, while the share of the world market will be 33% (29%).

Interpretations:

The break-even analysis including export shows the great possibilities for the German economy to profit from the introduction of PV. As long as PV prices have not reached break-even in Germany a concentration on export activities would return higher profits. However from the past and other industry sectors it is well known that it is not possible to establish a strong export industry without a healthy local market in the beginning. The export numbers in the scenarios may seem quite high, but the wind energy industry shows that it is possible: In 2005 the German export quota raised from 50% to 64% and the share of the world market was 46%.[72]

4.5.2 Including Niche-markets

In the break-even analysis above only solar systems connected to a large electricity grid are regarded and therefore the price of the power exchanges is used as break-even price. But PV systems are also used in off-grid applications like solar home systems, PV-hybrid systems or mini-grids (also called small island systems with a capacity of 1-20 MW). A niche-market has to meet two conditions to be worth the inclusion in the break-even analysis: First the price of the energy which is replaced should be significantly higher than the break-even price used for public grids. Secondly the potential for PV capacity must be sufficiently high to have an impact on the global break-even analysis. Regarding these two conditions the niche-markets of mini-grids are in particular very interesting. PV could deliver about 25% of the energy production; the other 75% come from fossil fuels, wind, water power and biomass. On the one hand in this case PV replaces energy from diesel generators which have high electricity production costs and therefore a high break-even price. On the other hand the potential for PV capacities in these mini-grids is reasonably high with more than 120 GW today [Krewitt et al. 2005a]. Comparing this number to the global annual market of 1,7 GW in 2005 there are a lot of growth possibilities for PV in mini-grid markets. Apart from economical aspects a replacement of diesel generators also offers advantages like reduction of air and noise pollution as well as a big potential for CO_2 emission reductions.

4.5.2.1 Assumptions for the Break-even Analysis including Mini-grids

Mini-grid break-even price:
As PV replaces energy from big diesel generators, their costs are studied. Mainly there are 3 parts: Investment costs, operation and maintenance cost (O&M costs) and fuel costs. As investment costs are quite cheap at 200 €/kW, they only contribute with 0,012 Cent/kWh to the kWh costs.[73] The yearly maintenance costs are given in literature between 5-20% of the investment costs [Muselli 1999]. As in this analysis the lifetime is assumed very optimistically with 20.000 hours, the yearly O&M costs

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[72] Source:
http://www.wind-energie.de/fileadmin/dokumente/Presse_Hintergrund/Tabelle_Arbeit_und_Wirtschaft.pdf

[73] Lifetime : 20.000 hours (Source: [Muselli 1999]); Use: 10 hours/day; Annuity: 0,2195 (6%)

are assumed as 15%. This corresponds to 0,008 €/kWh. Because the fuel costs are the most important part of the costs, they have to be chosen carefully. The GTZ (Deutsche Gesellschaft für Technische Zusammenarbeit) presents in yearly studies the fuel prices of over 172 countries [GTZ 2005]. The result is a very large range of diesel prices in the different countries due to subsidies in one country or energy taxes in others. In this analysis the retail price of diesel in the United States (0,68 $/l or 0,52 €/l[74]) is used, because it may be considered as the international minimum benchmark for diesel without subsidies or energy taxes.[75] Due to the fact that the mini-grids are quite far away from the main cities a transport surplus is added of 0,05 €/l, which results in 0,57 €/l or 0,137 €/kWh fuel costs (the fuel consumption of modern big diesel generators is around 0,24 l/kWh[76]).

Therefore the break-even price of big diesel generators is 0,157 €/kWh. This is about 3 times as high as the break-even in normal electricity grids. According to the other break-even scenarios a yearly price increase of 2% of the break-even price is also assumed.

Mini-grid growth scenario:

Since mini-grids have a higher break-even price it should be the goal to install as much PV as possible in mini-grids as less learning investments have to be paid. Through an adequate feed-in tariff for mini-grids the incentive for private investors to install PV in mini-grids can be raised reasonably as it happened with normal grid-connected systems in countries like Germany and Spain.

The potential for PV in terms of existing mini-grids is estimated at 120 GW by [Krewitt et al. 2005a].[77] Due to the fact that about 2 billion people are without electricity today, it is not too optimistic to assume that the potential for PV in mini-grids can be doubled before the year 2030 to about 240 GW. In the proposed scenario a very fast growth of PV systems in mini-grids is expected. It is assumed that in the year 2010 50% of the global annual installed PV systems will be installed in mini-grids. This percentage could be maintained until 2020 and from 2021-2030 this number is reduced to 25%. To keep the possibility of a direct comparison in the scenario $\text{Growth}_{\text{mini-grid}}$ the total

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[74] Exchange rate: 1 € = 1,3 $

[75] The diesel price depends on the benchmark of crude oil on the world market. In this work a price of 60 $/Barrel is assumed as an optimistic value.

[76] Sources: http://www.henkelhausen.de/NEU-M6-PROSPEKT.PDF; http://www.deutz.de

[77] In [Krewitt et al. 2005a] an analysis is presented about the installed volume of power plants smaller than 20 MW. From these numbers the PV potential in mini-grids is derived.

worldwide growth is the same as in the scenario $\text{Growth}_{\text{global, 1}}$, just divided in a grid-connected and a mini-grid part.

4.5.2.2 Results

The results show a huge reduction of learning-investments and both the break-even point and the win point are reached a lot earlier. The analysis was made with the $\text{Disc}_1/\text{PR}_{0,8}/\text{BEP}_1/\text{Growth}_{\text{global,1}}/\text{Growth}_{\text{mini-grid}}$ data.

Results Mini-Grid	**Mini-Grid**	**Large-Grid**	**Total (Mini + Large Grid)**	**Results Global**
Break-even Point				
Year	2013	2025	2017	2025
Disc. Learning Cost in Billion $€_{2005}$	14	120	78	204
Cum. Capacity in GW	21	318	69	478
Win Point				
Year	2016	2034	2026	2037
Cumulative Capacity in GW	45	1004	365	1580

Table 4-24: Results niche-markets mini-grids

Looking at both markets together the year of break-even improves from 2025 to 2017 and the discounted learning costs are reduced to 78 billion $€_{2005}$. Also the necessary cumulative capacities are many times lower than at the standard global growth scenario. If taking a look only at the part of the mini-grids, this niche-market will reach break-even in the year 2013 and only 14 billion $€_{2005}$ of learning investments are required. From this point on PV electricity will be cheaper than electricity of diesel generators and no feed-in law for mini-grid markets will be necessary any more. Also it can be seen that there is still much potential for PV installation in mini-grids remaining so there exists no capacity problem. The results are also given in the following graph:

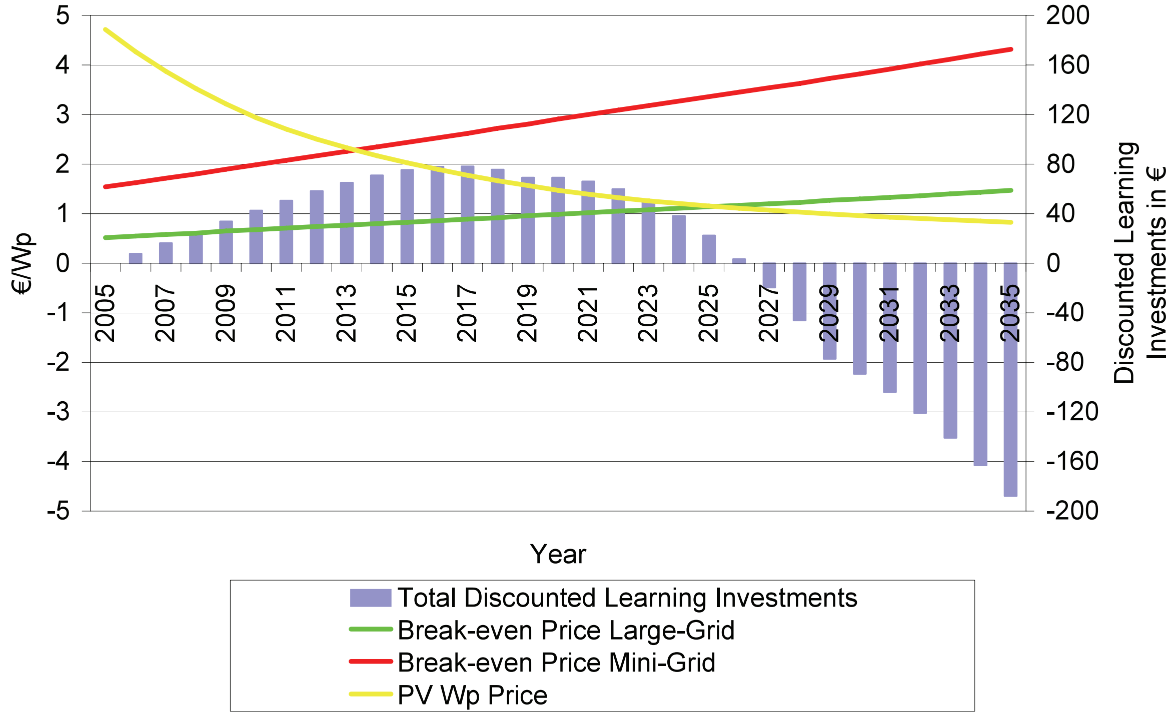

Figure 4-10: Results niche-markets mini-grids in €$_{2005}$

Interpretations:

Although assuming very optimistic values for a cheap production of electricity from diesel generators, the analysis indicates that PV power will soon be able to compete in the mini-grids without any financial incentives. Installing the same amount of PV systems not only in large-grids with relatively low break-even prices but also in mini-grids with higher break-even prices has dramatic impact on the economic analysis.

In the analysis of [Krewitt et al. 2005a] niche-markets are assumed to grow with the same annual growth rate as the world market and therefore the effect of mini-grid markets is nearly negligible with only 2% share of the annual global PV installations. In the analysis of this work, a very fast growth of niche-markets until the year 2010 is assumed. It has to be discussed under which conditions this growth can be possible. The necessary learning investments, although they are comparably small, will not be raised by the niche-markets themselves. It should therefore be an international goal of PV energy policy to support the affected governments to open their mini-grid markets for foreign investments. This could be done in form of feed-in tariffs which are paid by the international community and in combination with Clean Development Mechanisms (CDM) of the Kyoto protocol, which rewards the saved CO_2 emissions.

4.6 Conclusions

In this chapter, the concept of break-even scenarios has been explained. After completing the literature overview the value of PV in the public grid has been researched with PV production and price profiles. The presented break-even model has been used to calculate a variety of different scenarios for global and local markets, varying growth rates, progress ratios, discount rates and break-even prices. Finally an export orientated and niche-market scenario have been examined. The main results of this chapter are summarised below:

Determination of appropriate break-even price:
Break-even price is crucial for the calculation of learning investments. It has been shown that there are different means of determining the break-even price for PV. Because of hourly variations in electricity prices it has been argued that the best way to find the value of PV in the public grid is by the use of PV production profiles combined with power exchange price data. In any case a comparison of only production costs on the PV side and break-even prices including taxes (like end consumer prices) would lead to erroneous results.

PV production profiles:
The analysis of German PV production profiles of the year 2005 has returned energy earnings ranging from 859 kWh/kWp in the north of Germany to 1092 kWh/kWp in the South. Regarding the monthly distribution of the energy earnings it has been highlighted that 90% of the solar energy was produced in the months March to October. This means that energy prices of the months November to February nearly have no influence on the value of PV in the public grid in Germany.

The value of PV in the public grid and the development of electricity prices:
The volatility of electricity prices has been considerable in recent years, with a strong tendency of prices to increase. Although there are some arguments that this could be due to a monopoly like structure of the energy production sector in Germany, it has been shown that this is not only a sole effect of the German market, but occurred in all important European electricity markets. The combination of an extensive PV production database (including PV systems of more than 10 MW) with power exchange price data from the EEX has returned a value of PV in the public grid of 0,053 $€_{2005}$/kWh for the year 2005. This can be seen as a pessimistic lower limit since initial price indications in 2006 and the future market showed an expectation that prices would increase further (Futures are traded at 59 €/MWh to 82 €/MWh). For this reason and because of high insecurity in the development of the energy prices, three

different scenarios for the development of break-even prices are used in break-even analysis.

Inclusion of external energy production costs:
Since fossil energy resources, through their emissions, incur external costs which were not included in the price of the sold energy, the introduction of CO_2 allowances in 2005 was a step towards fairer competition. It has been shown that CO_2 allowances directly influence electricity prices even though they were given without cost to CO_2 producers in the first allocation round. This leads to an inclusion of external costs in the electricity price. In the break-even analysis the conservative approach is used of applying only electricity prices and not adding a further surcharge for external costs in order to avoid double counting of external costs. Energy policy should account for steadily increasing CO_2 allowance prices though continuously reducing the number of circulating CO_2 allowances. Equally important, they should not be given to producers for free, but rather they should be sold in auctions to avoid windfall profits. These measures will lead to fairer competition between the different energy technologies and will be important for PV to reach competitiveness.

Discount rates:
While discounting of future cash flows has no influence on the year of break-even for the year of the win point it is important. In the literature overview, studies are mentioned which do not discount future cash flows at all. This leads to an overestimating of the values of future gains of PV. It has been shown that the concept of social discount rate (mostly estimated at 3,5%) is questioned through the new concept of declining discount rates. Therefore both variants are used in break-even analysis. With declining discount rates the discounted learning investments required to reach break-even are slightly higher, but on the other hand the discounted profits in the year 2050 are significantly better (nearly twice the amount), although leaving all other variables unchanged.

Global learning investments and profits:
On the basis that PV gets to a share of at least 10% in the global electricity mix in the year 2050 and progress ratios of the PV systems' price are 75-80%, the economy will always profit from the introduction of PV. However this will also be the case if break-even prices increase by as little as 1% per year. The break-even point in these cases when PV becomes competitive, is always before the year 2033, most likely around the year 2025. In the case of a progress ratio of 85% the majority of the growth and break-even price scenarios return no profits for PV before the year 2050. The

discounted learning costs are on average 100 bn $€_{2005}$ for a progress ratio of 75%, 200 bn $€_{2005}$ for a progress ratio of 80% and 400 bn $€_{2005}$ for a progress ratio of 85%. These numbers may seem very large, but are less than 1% related to the worldwide gross domestic product in 2005 of 44.433 bn US$.[78] It is important to remember that these learning investments will be regained over the years and not be lost, if the win point is reached. Higher break-even prices favour the economic benefit of PV, but also slowly increasing energy prices would not prohibit the economic success of PV.

German local market needs export option:
Break-even analysis for the local German market has highlighted the problem of limited growth opportunities in combination with higher PV kWh prices due to worsening climate conditions. If the German annual market grows by 20% per year until 2020, there will be about 50 GW installed and break-even could still not be reached. The learning investments could only be regained until the year 2050 if the main market growth was to occur after reaching break-even in the years 2025-2030. The situation changes dramatically when including export possibilities in the scenario. If the local market continues to grow with the same speed as the global market and the difference between production and installation goes into export, in every scenario the learning investments will be regained and reasonable profit made by the German economy (in the year 2050: 53-251 bn $€_{2005}$ depending on the scenario) . The important consequence of this analysis is the energy policy that is restricted to the German market as the renewable energy law (EEG) is not sufficient to guarantee that the German economy will profit from the introduction of PV in the energy mix. Strong export incentives in cooperation with other markets are therefore necessary.

Mini-grid niche-market could lower learning investments:
In the section of the niche-markets it has been shown that a different growth velocity of PV in mini-grids will have a dramatic impact on the necessary global learning investments. By way of a break-even price which is about three times as high as in the large grid (0,15 €/kWh), the break-even point in mini-grids could be reached within less than 10 years and the win point only a few years later. The analysis demonstrates that from the economic point of view mechanisms should be started to help the affected regions to raise the share of PV in mini-grids reasonably in the coming years. On a global scale this will save a huge amount in learning investments (about 75% compared to the standard scenario).

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[78] Source: International Monetary Fund, World Economic Outlook Database, April 2006 in http://en.wikipedia.org/wiki/List_of_countries_by_GDP_%28nominal%29

5 Interpretations and Recommendations

This thesis has researched the price development of PV along with experience curve methodology. All work undertaken has concentrated on past price decreases of PV and on the development of the break-even model for scenarios into the future. The main results showed that past price decreases of PV were underestimated, due to a neglect of certain factors, which also influence the PV kWh price. Furthermore it has been shown that the introduction of PV in the electricity mix is economically beneficial and that the necessary learning investments are acceptable. Moreover a diffusion of PV including niche-markets on a global scale would result in a higher profit.

The literature overview at the beginning of this work has shown that so far, only module or BOS or PV system prices had been used for the construction of PV experience curves. Technological advances that influence the PV kWh price and are not included within the investment costs, had not been investigated so far. Therefore the main emphasis of the experience curve research of this work has been the analysis of the so called “soft factors”, which influence the PV kWh price, for example, lifetime of the system, energy degradation or performance ratio, variable costs and so on.

In a sensitivity test it has been demonstrated which influence has every single factor on the kWh price. The results are that there exists a great interrelationship between all factors. For example the effect of a extension of the system lifetime depends very much on the imputed interest which is used. Although every soft factor on its own has little influence, the combined change of soft factors at the same time returns greater effects on the PV kWh price (see Table 3-1). With this theoretical background, the soft factor changes in the last 15 years of PV development have been researched in literature to include empirical data in the experience curve construction. The main challenge of this research work has been a lack of publications due to the long term aspect of studies dealing with soft factors.

As a result of varying growth velocities within the local German and indeed the global market, the effects of the use of different cumulative capacities was analysed in detail. As PV systems and kWh prices are combined systems with some components that learn on a global basis and other components that learn on a local basis, both cumulative references have been used for the construction of experience curves. It has been pointed out that this problem will be reduced in the near future due to an expanding PV market where an equalisation in growth rates is expected.

The results of the experience curves analysis have shown that using kWh prices instead of only module or PV system prices confirm an improvement in progress ratio of 6%-10% to values of 65,6%-81,2%. This is a reasonable decrease in the progress ratio, but also requires much more in-depth calculation and takes account of insecurity about soft factor change. In an exemplary extrapolation of the kWh and the PV systems experience curve, it has been demonstrated that the error in the price decrease prediction of PV can be up to 40% over the next 15 years, if using only installation price data. For future work it is recommended that every researcher decides whether to use more complex calculation methods with soft factor changes or to reduce the obtained progress ratio of PV systems by an estimated factor.

In the break-even analysis of this thesis the complex method of including soft factor changes has been used. However before starting with the analysis itself, the concept has been explained, the use of terms has been clarified and an overview of different methods of obtaining break-even prices of PV have been presented. In addition some studies, that only deal with break-even issues have been summarised and discussed. The literature overview has shown that there is no consensus about the value of PV in the public grid and there exists disorientation of how future cash flows must be treated in a break-even model.

This thesis therefore contributes to the discussion of the value of PV through the detailed analysis of hourly PV production data of more than 10 MW PV systems in Germany in combination of hourly price data of the European power exchange (EEX). On the one hand the EEX data is regarded as highly representative because approximately 17% of Germany's electricity consumption in 2005 was traded over the EEX. On the other hand the hourly production data of more than 1000 PV installations is a very good sample for the analysis because of its unique size and because it was counted online and cross-checked by Meteocontrol.[79] The result for the value of PV in the public grid in 2005 is 0,053 $€_{2005}$/kWh, which is quite close to the peak power price at the EEX (from 9-20 hours). It should be underlined that no indications have been found that a higher break-even price for PV, other than the average peak power price can be justified.

Since 2005 CO_2 allowances are necessary for fossil power production and a strong correlation between CO_2 allowances and the electricity prices has been found. It explains that external costs are starting to be internalised in the traded electricity price. Due to double counting of external costs in the break-even model, no further

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[79] see http://www.meteocontrol.de

surcharge on the break-even value of PV has been added for the use in the break-even analysis. In principle the internalisation of external costs in the electricity price is welcomed, but the distribution of free CO_2 allowances to the producers is strongly criticised and an auction model is recommended.

The developed break-even model is able to simulate different scenarios not only on a global scale but at the same time for a local market (in this case, the German market). The use of different discounting schemes, variable break-even prices and including soft factor changes – based on kWh calculation – are but a few advantages of the break-even model. Special attention has been paid to the method of discounting future cash flows as this point is often disregarded. The comparison of the social discount rate with the new approach of declining discount rates has shown that it is justified to assume higher profits from the introduction of PV, if the use of declining discount rates in long term models is to be standard.

In this work different break-even scenarios have been discussed, but the results all point in the same direction: In the large part of global scenarios the profits of introducing PV will be reasonable if a progress ratio of PV systems of at least 80% can be maintained. There have to be investments of 100-400 billion $€_{2005}$ if break-even point is to be reached. This is when PV becomes competitive. But even assuming slowly increasing energy prices, these learning investments can be regained and the economy will profit from the introduction of PV.

The situation is even more favourable if it is possible to use the niche-market of mini-grids in the initial years for the diffusion of PV. Due to elevated break-even costs of more than 0,15 $€_{2005}$/kWh, break-even point is reached within the next ten years. This can reduce learning investments for the standard scenario from 204 to 78 billion $€_{2005}$.

The situation regarding the local German market is more difficult. Due to the fact that the PV share in the electricity mix can not be raised without limit, the growth possibilities for PV inside Germany are also limited (surface limits still do not affect). This leads to a situation in which learning investments in most scenarios cannot be regained if no export possibilities are regarded. The alternative local scenario including export shows a big difference. Although assuming only 50% of added value for the exports, the German economy will profit from the introduction of PV in every scenario.

Regarding the results of both alternative scenarios, the idea suggests itself that a combination of an export strategy with a feed-in tariff for mini-grids should be a goal for energy policy. For both partners, the exporting nations and the countries of the mini-grids, a feed-in tariff partly paid through financial funds from exporting nations would have significant advantages. On the one hand exporting nations could solve the problem of limited growth possibilities and would start to open important markets for the export efforts. On the other hand the "mini-grids" countries would receive help towards learning investments since they would not be able to raise the necessary funds on their own. In addition they would have the advantages of a clean, secure and sustainable energy source. On a global scale two more objectives would be realised: The necessary learning investments would be reduced to a minimum and a maximum of CO_2 emission reduction would be reached due to the replacement of diesel generator technology.

Recommendation for future work:
It is probable that PV technology will continue its rapid development into the future. Firstly it is imperative that more research in the field of PV experience curves and break-even models is done in order to achieve more precise results and reduce uncertainties. Therefore the following recommendations for future work are proposed:

- Intensifying soft factor research and reducing uncertainties of soft factor development.
- Constructing PV experience curves for different technologies like thin film and analysing the soft factor change of each technology separately.
- Extending the calculation of PV value: As PV uses no fuel there is no risk of future price changes. Reduced risk of PV or elevated risk because of high volatility of fuel prices of other energy production methods should be quantified and included in the break-even analysis.
- Developing a program for a feed-in tariff in mini-grids supported by exporting nations like Germany, together with Clean Development Mechanisms (CDMs) of the Kyoto protocol.
- Using probabilities for different growth and break-even scenarios for the restriction of the variability of simulation results.

Many aspects of PV experience curve and break-even analysis have been analysed and discussed during this work. The aforementioned points indicate that new questions have arisen and should be the subject of further research.

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