DIFFERENTIATED PRICE EXPERIENCE CURVES AS EVALUATION TOOL FOR JUDGING THE FURTHER DEVELOPMENT OF CRYSTALLINE SILICON AND THIN FILM PV SOLAR ELECTRICITY PRODUCTS

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ABSTRACT: Decades of research have demonstrated how several industries related to PV solar – semiconductors and flat panel displays, among others – have generated steady and predictable declines in the "price experience curve" (PEC) and Price Experience Factor (PEF). This paper analyzes factors that apply to PV solar in order to project expected cost and price declines from the present towards 2020. Thin film technology offers a somewhat greater potential decline of module cost and price compared to crystalline silicon technology, due to its technological similarity to flat panel displays and the cost-cutting potential of large-area substrates. However, the higher efficiency of c-Si PV modules may offset that advantage when overall system cost and price is considered. Ultimately, the decline for both cost curves should prove to be quite significant and therefore enable increased and widespread adoption of PV technology for a variety of applications.

1 INTRODUCTION: LEARNING AND EXPERIENCE CURVES – THEORY AND EXAMPLES

The phrase "learning curve" was first used in the end of the 19th century by the German psychologist Hermann Ebbinghaus [1] when making experiments on how fast human beings learn information. The first quantitative description is linked to an observation by T. Wright [2] from the Wright-Patterson Air Force Base in US in the early 1930s that every time the total aircraft production doubled, the required labor time decreased by a constant percentage, which was in this case 10–15% (the learning factor).[A]

The term "experience curve" was used later in a much broader scope. It states that each time the cumulative volume of produced goods or a service doubles, the value added costs fall by a constant and predictable percentage (the experience factor). If one plots (Fig. 1) in a double logarithmic scale the number of units on the x-axis and the cost on the y-axis one obtains a straight line, where the slope represents the experience factor.

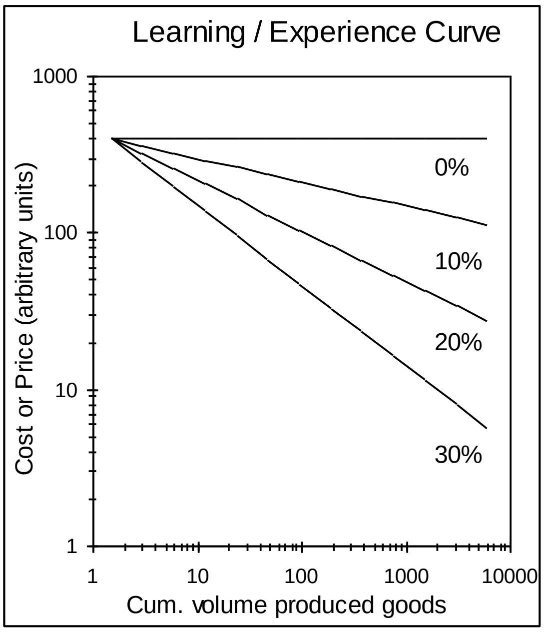


Fig.1: Schematics of Experience Curves

This was first described for single products or services in a single company. In the late 1960s Bruce Henderson of the Boston Consulting Group (BCG) began to emphasize the implication of the experience curve for strategic considerations [3]. Research by BCG in the 1970s observed experience factors for various industries that ranged from a few percent up to 30%. One of the proposals of BCG to consulted companies was that this predictable cost decrease should be passed to the respective price development.

This graph is called a "price experience curve" (PEC). It was also found that for a specific product a straight line was not only obtained for a single company but also when one plots the global average price versus the globally produced cumulated number of units. Although there are many factors additionally influencing this PEC, it is remarkable that in most cases this straight line quite often follows several orders of magnitude.

PECs do not show a time scale, but only a cumulative volume. This becomes important when extrapolating to the future. A time, when a new cumulative volume is reached, can only be derived by assuming a particular growth rate.

An impressive PEC is shown in Fig. 2 for the DRAM semiconductor price per bit as a function of the cumulative bits produced over the last 30 years [4].

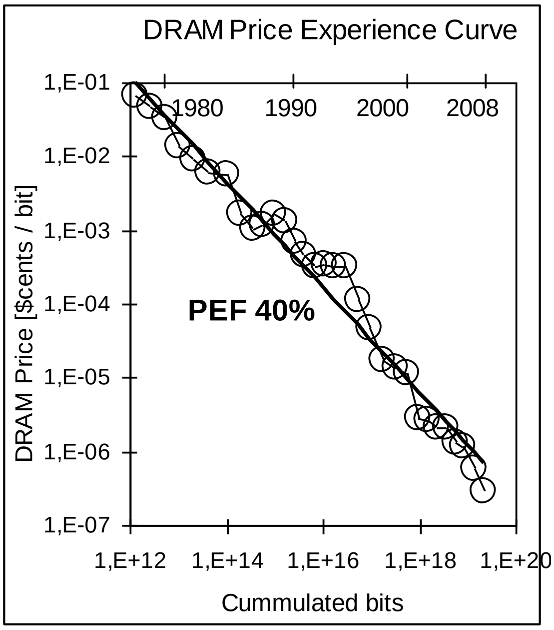
For more than 5 orders of magnitude, the price declined with a Price Experience Factor (PEF) of about 40% every time the cumulative volume doubled; this corresponds to an average price decline of about 33% per year. This behavior is technologically driven by the well known Moore's law in the semiconductor industry (doubling of the number of bit cells per unit area every 1.5 years) [B]. Fig. 2(b) indicates the respective times, where a new so-called technology node was introduced. The latter is thereby described by the smallest technology dimension applied on the chip.

It is often argued that such a high PEF of about 40%

as observed for the DRAM bits is only possible because of the miniaturization techniques applied in the semiconductor industry. A remarkable PEC for a product which increased substantially in size over the last 20 years is shown in Fig. 3 [5].

The need for Flat Panel Displays (FPD) began with the need to have flat plate displays for mobile phones and laptop computers which could not be done with the CRT (cathode ray tube) technology. Starting in the early 1990s with a substrate size of 0.1m² the technology for the TFT-LCDs (thin film transistor-liquid crystal display) developed continuously towards 1.4m² (Generation 5) and more recently to more than 5m² (Generation 8), while the technology for the next generation of 10m² has already been announced by display manufacturers. It is interesting to note that the PEF for this product is an astonishing 35%. This is due to the fact that most of the value-added steps profited significantly by the volume and size development.

One general observation is that for many different products the same slope for the respective PEC is seen with no discontinuity for the product in consideration. In



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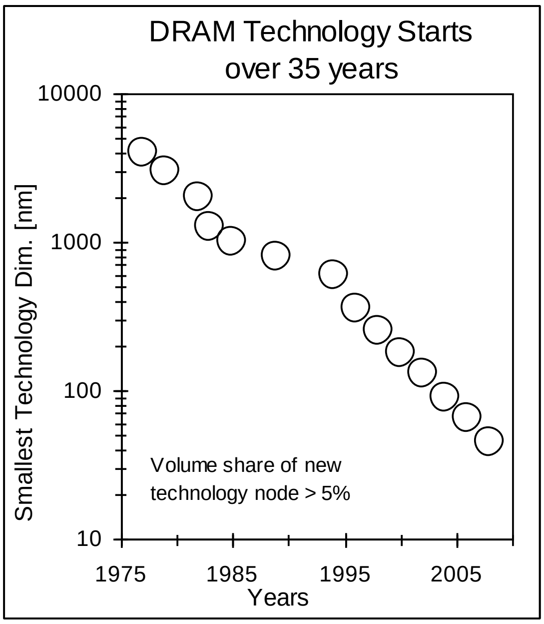

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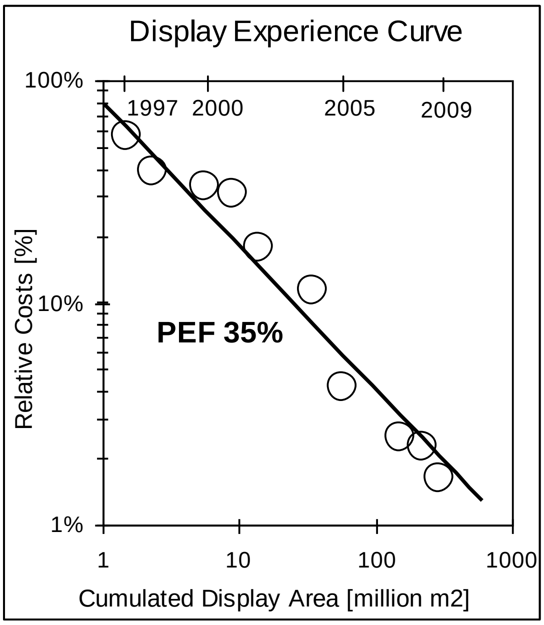
Fig. 2: DRAM semiconductor industry: (a) Price Experience Curve and (b) Technology nodes as a function of time



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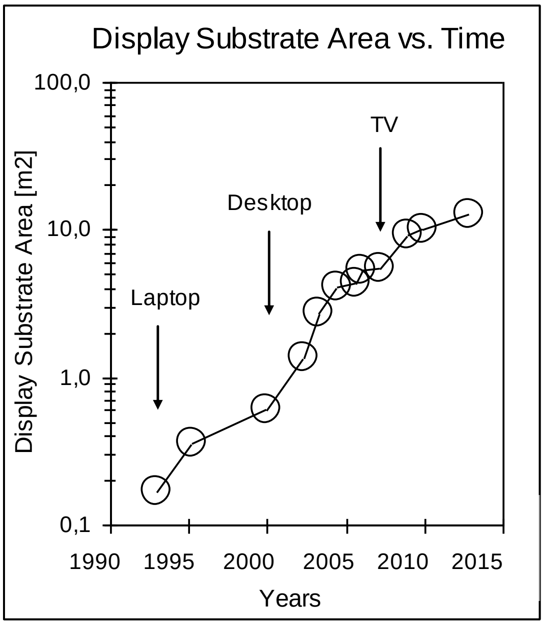

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Fig. 3: Flat panel display: (a) Experience Curve and (b) substrate size increase as a function of time

the case of the PEC for the DRAM semiconductor, the natural start of the PEC was with the development of the first solid state transistor, which was a breakthrough technology that largely replaced vacuum tubes. Since then, the basic transistor design has remained very much the same, despite the fact that many inventions have taken place. The curve may end in the future when the level of individual atoms in the solid state device is reached and a radically new type of switching device will be developed. The same may be true for display products: this PEC may see its end if future OLED (organic light emitting diodes) products show first better performance and with subsequent scaling in volume also lower the cost and price of OLED based FPDs.

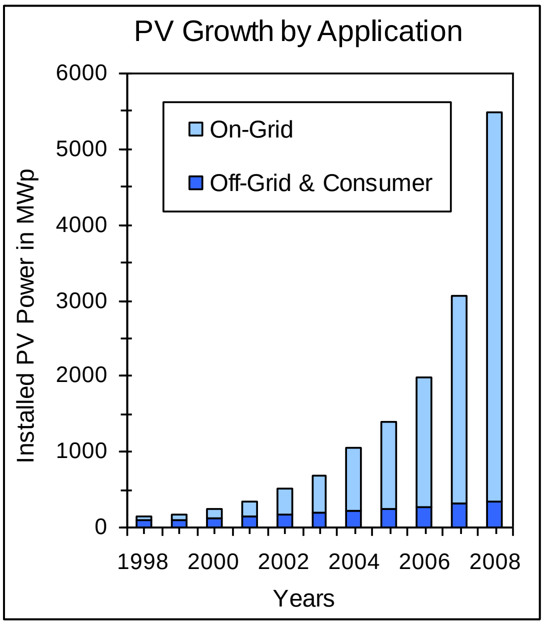
Just for comparison: a PEC for the coating process of architectural glass (low E) shows a PEF of about 17% for the last 25 years, mainly driven by the increase of substrate size and continuous optimization of large-area PVD (physical vapor deposition) coating equipment with a maximum glass size today of 3.21m x 6m. For standard float glass with more than 3mm thickness no major price reduction was experienced in the last years; therefore, the PEC for a complete window glass system composed of one bare float glass and one coated glass is even further decreased towards a value far below 10% [6].

Qualitatively it can be stated that the higher the technology contribution and the lower the material cost part of the production cost of a product is, the higher the PEF; it decreases as the material and energy cost covers more and more the total production cost of a product.

2 PV SOLAR ELECTRICITY: HISTORY, PRODUCTS AND PRICE EXPERIENCE CURVE

PV solar electricity is an elegant method to produce electricity, by converting solar energy using semiconductor materials. Being modular by nature, PV solar spans a power range of several orders of magnitude: small consumer systems in the range of several watts; rural electrification producing several hundred watts; and grid connected systems in the kW range for household use up to hundreds of MW for peak power utility applications. The various customer needs will be served by different technologies. It is worthwhile to note that when making future projections of the PV market one should analyze these various market segments in the various regions in the world in order to arrive at a first approximation as to which specific technologies are best suited for the respective need and volume. The historic market growth within the last 10 years is seen in Fig. 4, both in terms of application (a) and regional installations (b).

The last 10 years, with an aggregated growth of 45% per annum, have seen a reversal in the volume share of the grid-connected systems versus consumer and rural off-grid electrification: in 1998 about three quarter of installations was off-grid, while in 2008 more than 90% were grid-connected systems. The market growth of the latter was an astonishing 59% per annum, driven by a variety of market support programs. As seen in Fig. 5b, this support was first seen with installations in Japan (70.000 roof program), followed by the various feed-in tariff (FiT) programs starting in Germany in 2000, Spain



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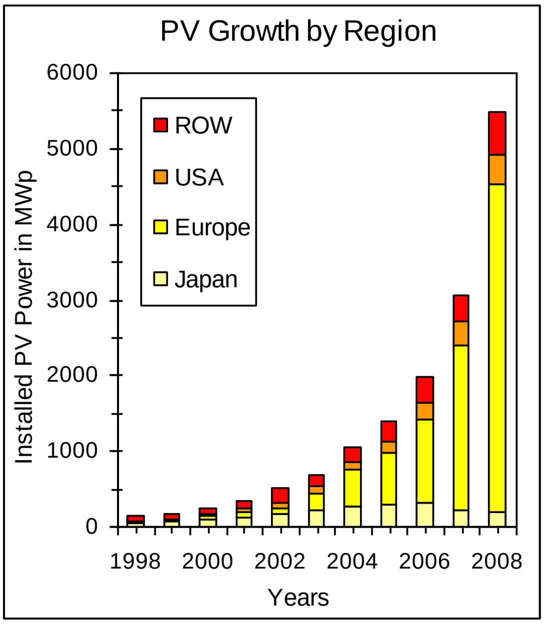
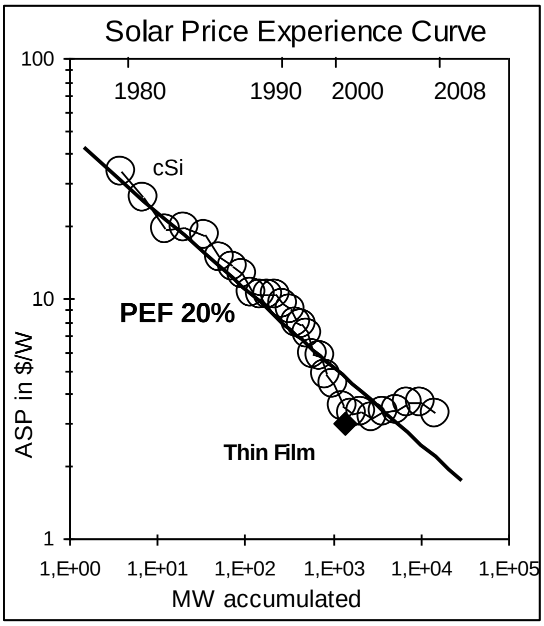


(b)

Fig. 4: PV market growth: (a) by application and (b) by regional installations, source [7]

in 2007 and Italy, France and many others now. As these FiT support programs are backed politically it is imperative to show which cost and price development can be foreseen for PV systems, especially in the grid-connected area. Obviously PECs can make an important contribution in this critical discussion.

For some time the PEC for PV modules has been followed by Strategies Unlimited (today Navigant) and Paul Maycock [8] in the US. Until recently the vast majority of PV modules were based on crystalline Silicon (c-Si) technology. The corresponding PEC is shown in Fig. 5a, which shows a PEF of 20%. [C].



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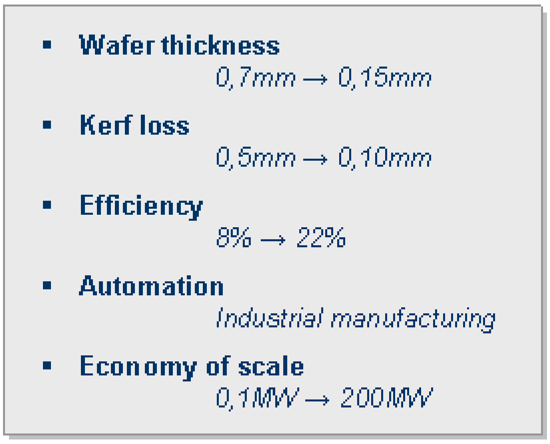

(b)

Fig. 5: Historical Price development of Solar modules: (a) PEC [9] and (b) technology factors driven the PEC

The recent deviation from the straight PEC line was predominantly due to higher market demand and a lack of sufficient production capacity. A major factor limiting production in the past couple of years was the limited volume of silicon feedstock with an associated high price, especially in the spot market. This increased cost could be passed on as a higher price due to a seller's market. Since late 2008 this situation has changed quite considerably:

(1) The big chemical companies significantly increased their poly-Si output capacity, and a number of new market entrants added capacity.

(2) Thin-film PV modules entered the market in significant quantities with a price level lower than c-Si modules, although they were starting with a relatively small cumulative volume (1,4 GW) compared to c-Si (13,4 GW) at the end of 2008.

(3) The market growth in 2009 will be much smaller compared to 2008

(4) The increase in capacity has led to a buyer's market.

The PEC in Fig. 5a ends with quoted price numbers for c-Si at the end of 2008. Until now (September 2009) we have seen a further price decrease and a quick return for c-Si modules towards the "old" PEC as already experienced in other technologies (semiconductor, display). Further price development for the added cSi volumes will most likely follow the extrapolated PEC at least for another order of magnitude as seen from earlier studies [10].

Only recently a new type of solar module, the Thin Film type, has entered the power marketplace in larger quantities. It is interesting to note that this module class is already showing at a much smaller cumulative volume a lower cost and price compared to c-Si modules. An average price of Thin Film modules for 2008 is shown as a single square in Fig. 5. In a previous analysis, Martin Green pronounced the potential of Thin Film to stay at a lower price level compared to c-Si and to drive further down a continuous price reduction on a long term [11].

If one compares the production technologies for c-Si and thin film (TF) modules in general terms, there is a profound difference (see Fig. 6). The basic value-added steps for c-Si are: crystallization of Si, manufacturing of heavy weight ingots, wafering, cell production starting with texturing till sintering, interconnect of cells to strings and module completion. The basic value-add for TF products involves the large-area deposition of the front- and back contact, as well as the absorbing and charge-separation layer with three subsequent scribing steps (mainly laser, but also mechanical) to directly create the series-connected raw module. This is the case both for the illustrated superstrate technology (TF Si) as well as for the substrate technology (II-IV compounds). For the purpose of this paper it is not necessary to differentiate within the various c-Si and TF technology variants, respectively (c-Si with mono-crystalline and multi-crystalline technologies, TF with amorphous, amorphous/microcrystalline, CTS and CI(G)S technologies).

The interesting question arises: which price development will be experienced in coming years for the two different technologies, if different growth rates for c-Si and TF occur (= different cumulative volumes at a given time). Considering the above shown value added chain for Thin Film there is no considerable price reduction expected from the large substrate glass [6]. A major contribution will most likely come from the formation of the thin film layers. As mentioned above, glass coating showed a PEF of about 15% and this was mainly due to increasing glass dimensions and equipment capacities. For PV Thin Film, efficiency is an additional important parameter that is assumed to further enhance the PEF as experienced for c-Si. A different PEF for TF modules may happen if we compare their production technology with flat panel display products: for FPDs, the increase in substrate size enabled a quick cost and price decrease with appropriate learning and cumulative volume resulting in a PEF of even 35%. The possible consequences on the Thin Film PEF are analyzed in more detail in the next section.

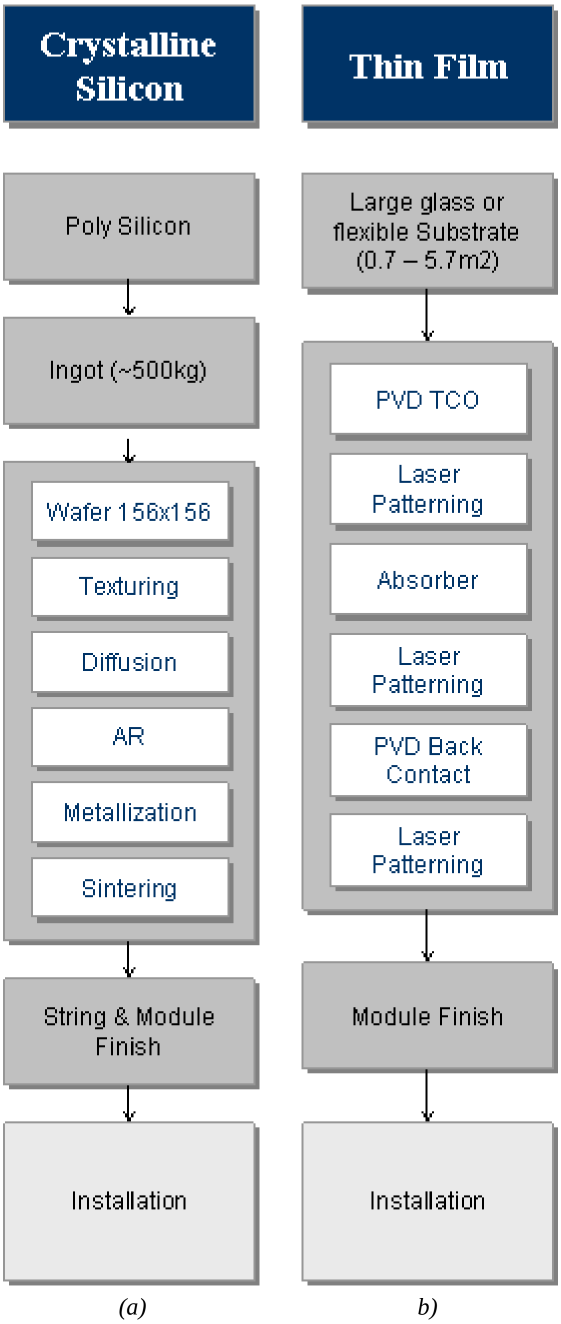

Fig. 6: Value added steps for (a) c-Si modules and (b) Thin Film modules

3 PV PARAMETER VARIATION AND RESULTS

In order to calculate possible future cumulative volumes for the PV market in general, two growth scenarios developed in a recent study by EPIA were chosen [12]: these two projections form a baseline as well as a paradigm shift scenario. The `baseline scenario' uses growth numbers in a business-as-usual manner (25% average growth rate p.a.). It projects that about 4% of Europe's electricity needs to be generated by PV in 2020 (cumulative installations of 130 GW producing 154 TWh of electricity). Further assuming that in a global context, 40% of the global installations are done in the EU territory, this gives 87 GW of new installations worldwide in 2020. The second 'paradigm shift' scenario uses an average growth of 34% annually, leading to an annual worldwide installation of 163 GW in the year 2020. This gives 390 GW cumulative installations in Europe, providing 12 % electricity (462 TWh) in 2020.

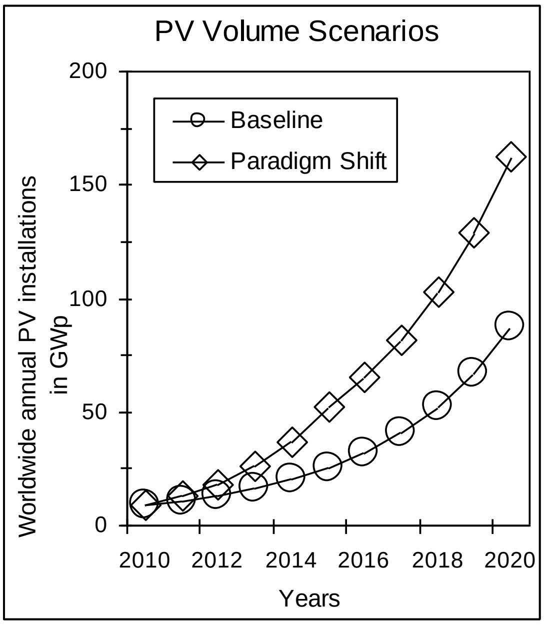

Fig. 7: PV Volume Scenarios based on "Set for 2020" (EPIA, 2009), [12] and [D]

In the following parameter variation exercise, summarized in Table 1, the volume share of TF and the PEF for TF is varied for each of the two growth scenarios. This results into eight different cases.

PV volume growth scenario	Baseline				Paradigm shift			
Thin Film volume share	15%		15% → 35%		15%		15% → 35%	
Thin Film PEF	20%	25%	20%	25%	20%	25%	20%	25%
Case	1	2	3	4	5	6	7	8

Table 1: Different assumptions for volume growth, Thin Film technology share and PEF's till 2020 [12]

Within each growth scenarios there was either a constant TF volume share of 15% or an increase from 15% to 35% in 2020 assumed.

Additionally, the slope for the PEC for TF was first assumed to be the same PEF of 20% as in c-Si. By comparing solar module with FPD technology an increased value of 25% was considered. Without a very detailed understanding of analogies between TF and display products one should be hesitant to use higher PEF numbers for TF. The results are displayed in Fig. 8 and Fig. 9.

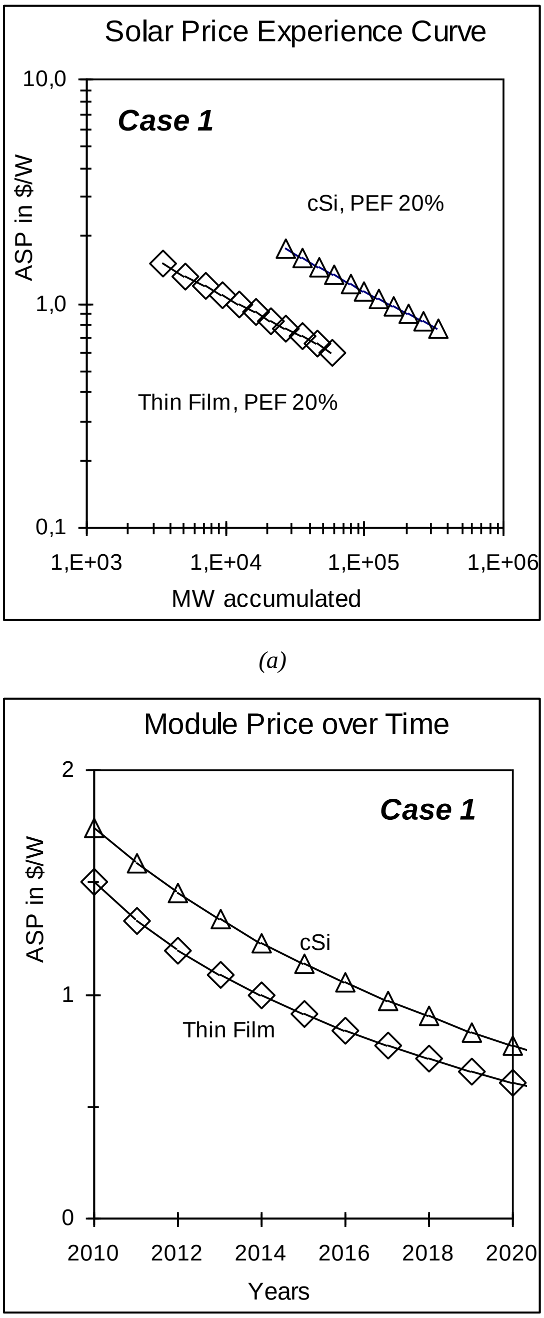

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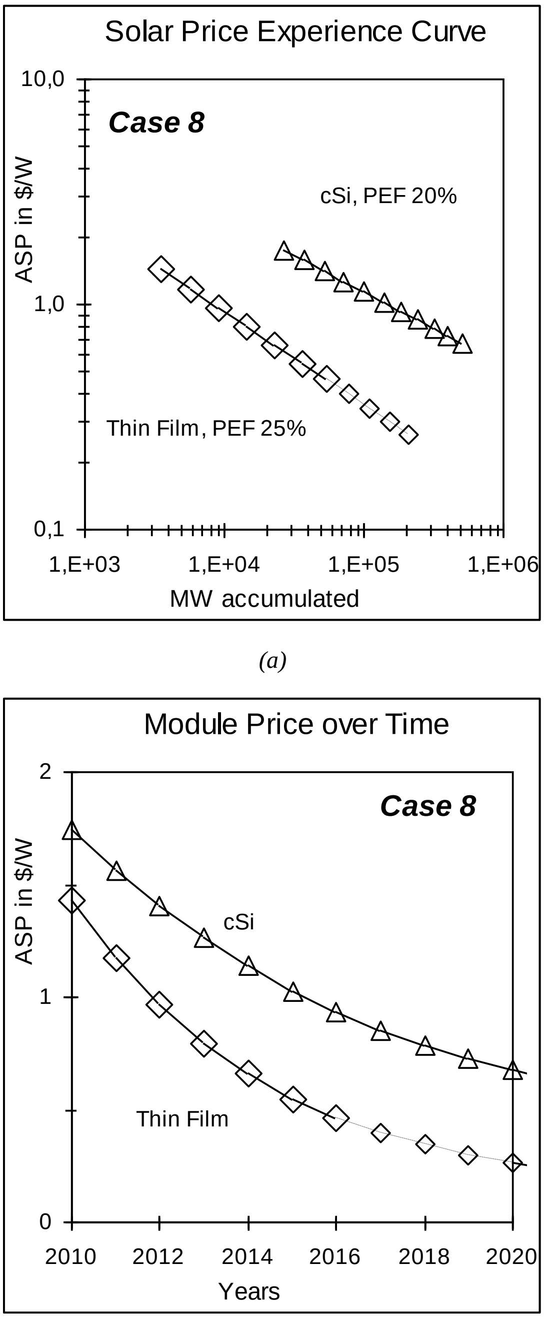
Fig 8: Case 1 – Price Experience Curve (a) and Price as a function of time (b)



(a)

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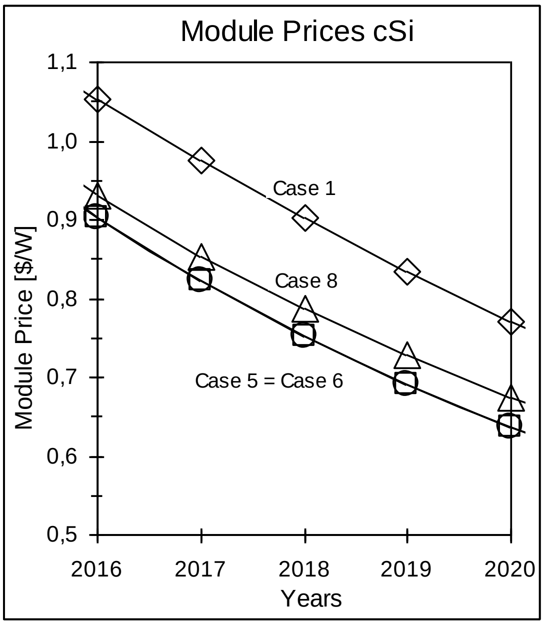
Fig 9: Case 8 – Price Experience Curve (a) and Price as a function of time (b)

For case 1 (lowest growth rate, constant TF share of 15% and same PEF of 20% for c-Si and TF) the calculated volume of c-Si was associated with the extrapolation of the PEC from Fig. 5a. For the TF curve the same slope was used and the end data points for c-Si and TF are for the year 2020, respectively. With the given set of parameters one can also plot the price development as function of time, as seen in Fig. 8b.

The same calculation was done for the other extreme case 8 (high growth rate, increased TF share from 15 to 35% and higher PEF of 25% for TF) and is shown in Fig. 9a for the two PEFs and in Fig. 9b for the price development for c-Si and TF, respectively [10]. It is evident that case 8 shows a much bigger increase in the difference of expected c-Si and TF price declines. But it is open whether prices significantly below 0,5$/W can be reached. For the cases 1, 5, 6 and 8 the prices from respective calculations are shown for easier recognition as function of time from 2016 to 2020 for c-Si (Fig. 10a) and TF (Fig. 10b).

As a summary the difference of expected prices for c-Si and TF as a function of time for the cases 1, 5, 6 and 8 is plotted in Fig. 11. The increase of the delta and the further decrease after 2013 for the different scenarios is



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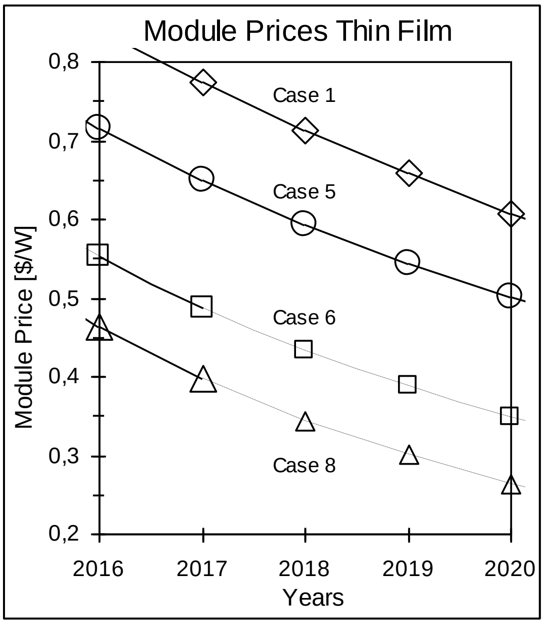

(b)

Fig 10: Module Prices for (a) cSi and (b) Thin Film for case 1, 5, 6 and 8

due to the quite complex transition from a double logarithmic PEC to a plot showing price as a function of time on a linear scale. For cases 1 and 5 (same TF share over time, but two growth scenarios) the Delta varies between 0.15 and 0.25 $/W. If for the high-growth scenario the high 25% PEF for TF is assumed (case 6 and 8) this Delta increases to values in-between 0.30 and 0.50 $/W.

A module price delta between TF and c-Si of between 0.10 up to 0.50 $/W is quite significant if related to the absolute prices in the range of 1.5 $/W in 2010 and decreasing towards 0.6 $/W and below in 2020. This difference alone would give reason to expect that TF modules would quickly dominate the market share in PV, if module price alone dictated the system price.

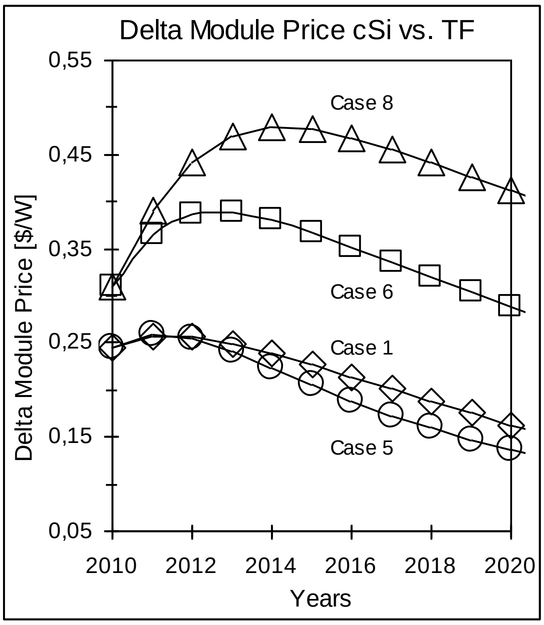

Fig. 11: Price Delta of c-Si modules versus TF modules for case 1, 5, 6 and 8

However, there is another important parameter, especially with utility-power applications: the area-related cost which is inversely proportional to the efficiency of the modules used. The total system price ‘P’ is

P(tot) = P(module) + P(power) + P(area) with:

P(module): module price ex-works as discussed in the previous sections, plus a margin for the installer

P(power): power-related costs like DC-AC inverters and some approval procedures

P(area): mounting structure, cabling and installation costs

Today the majority of c-Si modules show an efficiency of about 14-15% (based on total module area) [13], while TF modules have an efficiency of about 8-12%. Total prices in Germany today are seen in the range of about 3 €/W for medium-sized systems mainly with c-Si modules [E]. The end customer prices for the three components are approximately P(mod)=1.7 €/W, P(power)= 0.5 €/W and P(area)=0.8€/W. If one keeps the P(power) constant for a given system size and also the P(tot), one can calculate the needed module price as function of the module efficiency, since the P(area) is inversely proportional to the efficiency; a deeper analysis on area related costs for cSi and TF based modules was shown by Manfred Bächler [14].

A simple calculation for the dependency of the three parameters is shown in Fig. 11a. It can be easily seen that a module of lower efficiency will need a much lower price for a given efficiency gap, compared to an allowed module price increase for the same efficiency gap. In particular, for a 10% efficient TF module one would take from this graph a needed 0.3 €/W lower module price compared to a 14% c-Si module for the same total system price. This is comparable to the price differences as seen for the various scenarios. In power-related applications it is important to take into account which additional parameters are influencing the generation cost of a kWh. One such parameter which has to be added to this comparison is the different temperature coefficients for efficiency. This is highest for c-Si modules and lowest for a-Si TF modules; it becomes even more important since one has to carefully compare the respective installation sites and other parameters to find out which module technology best suits the respective application.

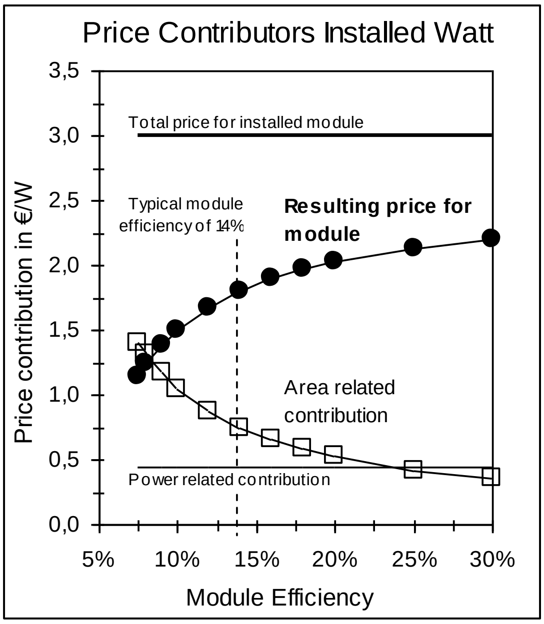

Fig. 12: Dependencies of price contributors for installed PV power on module efficiencies

5 COMMENTS

[A] The value of the learning factor is negative, e.g. -20% price reduction when doubling the volume. For easier discussion we will use in the following only the magnitude of this value. This value is also known as Price Experience factor (PEF).

[B] The first author remembers that during his study of physics in the early 1970s even industry experts and scientists did not expect silicon devices to continue this PEC curve due to properties of this material. At that time it was not foreseeable that photolithography would enable structures in the 100, 50 and today 20 nm scales to be used in large-scale manufacturing (nano-manufacturing).

[C] The shown prices are actual prices in the respective year. Thus, inflation is taken into account within the calculation of the Price Experience Factor. If one calculates the PEC backwards with 2008 basis and assuming an inflation rate of 3% for the past 30 years a PEF of only about 14% is achieved.

[D] In contrast to the historical data from NAVIGANT (see Fig.5) that consider off-grid and on-grid data, the growth scenarios from EPIA reflect only grid-connected volumes

[E] The current exchange rate is about 1.4 US$ / Euro

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