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The learning potential of photovoltaics: implications for energy policy

Bob van der Zwaan[a,b,*], Ari Rabl[c]

[a] Belfer Center for Science and International Affairs, Harvard University, Cambridge, MA, USA
[b] ECN, Energy research Centre of the Netherlands, Amsterdam, The Netherlands
[c] Centre d'Energétique, Ecole des Mines, Paris, France

Abstract

This article examines the prospects for cost reductions of flat panel photovoltaic (PV) electricity. Current PV production cost ranges are presented, in terms of cost per peak W and cost per kWh, for single crystalline and multi-crystalline silicon, as well as for thin-film technologies. Possible decreases of these costs are assessed, as expected based on learning curves. The cumulative production needed to reach 'breakeven' (at which PV is competitive with conventional alternatives) is estimated for a range of values of the learning curve parameter. The cost of this cumulative production is calculated, and the question is posed whether and how the 'cost cap' can be bridged, the latter being the difference between what this cumulative production will cost and what it would cost if it could be produced at a currently competitive level. We also estimate how much PV could gain if external costs (due to environmental and health damage) of energy were internalised, for example by an energy tax. The conclusions are: (1) mainly due its high costs, PV electricity is unlikely to play a major role in global energy supply and carbon emissions abatement before 2020, (2) extrapolating past learning curves, one can expect its costs to decrease significantly, so that a considerable PV electricity share world-wide could materialise after 2020, (3) niche-market applications, e.g. using stand-alone systems in remote areas, are crucial for continuing "the ride along the learning curve", (4) damage costs of conventional (fossil) power sources are considerable, and they could provide an important part of the rationale behind major policy efforts to encourage increased use of PV. The costs involved with such policies would be elevated, but a considerable share of these costs could be justified by the fact that conventional power damage costs constitute a significant fraction of the cost gap, although probably not enough to close it.

Keywords: Cost reductions; Photovoltaic electricity; Experience curves; PV; Cost gap; Environmental damage costs; External costs; Energy policy

1. Introduction

Photovoltaic (PV) systems offer the promise of clean and plentiful energy, but they suffer a large handicap in that their cost is still much too high. Nevertheless, during the 1980s and 1990s PV cell production has been increasing on average by more than 15% per year. During the sole year of 1999 nearly 200 MW_p[1] of solar cell modules were produced, such that at present about one GW_p capacity of PV is in operation globally, generating about 1 TWh a year. In the early 1990s solar home systems and village power systems accounted for some 20% of the PV market, while grid-connected PV systems accounted for 11%, and the remaining 69% originated from widely ranging applications, among which water pumping, communication, leisure and various consumer products (such as pocket calculators). Recently, the relative importance of grid-connected systems has been increasing considerably, to about a quarter of the current PV market. Compared to the 3300 GW total generating capacity installed world-wide (EIA, 2002), the contribution of PV is today still very small.

This article addresses a number of questions that are essential for making a proper analysis of the future prospects of PV:

- What is the current state-of-the-art and cost of flat panel PV technologies, and what is their prospect in terms of cost reductions?
- What is the cost gap (i.e. the excess cost of cumulative production above the breakeven cost) that needs to

*Corresponding author. BCSIA, John F. Kennedy School of Government, Harvard University, 79 John F. Kennedy Street, Cambridge, MA 02138, USA. Tel.: +1-617-496-9255; fax: +1-617-496-0606.

E-mail addresses: bob_vanderzwaan@harvard.edu, vanderzwaan@ecn.nl (B. van der Zwaan), rabl@cenerg.ensmp.fr (A. Rabl).

[1] The subscript p indicates the peak output when solar radiation = 1 kW/m^2. Stating costs per W_p is convenient because it obviates the need to specify area and efficiency separately.

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be bridged before these PV technologies become competitive with other energy technologies?

- How much could PV gain if external costs (due to environmental and health damages) of all energy sources were internalised, for example by an energy tax?
- How do the required PV learning investment costs compare to current PV expenditures?
- How do the costs of reaching economic breakeven for PV compare to the costs involved with the internalisation of the damage costs of e.g. fossil-fuelled electricity?

Here we consider only simple flat PV panels. Concentrating systems involve different technologies and cost characteristics, and are generally less suitable for the relatively small-scale applications that are more likely to dominate the market in the near term than large-scale use of solar energy.

2. State-of-the-art: PV technologies and their costs

The PV module, usually consisting of a number of solar cells, is the main component of a PV solar energy system. Solar cells can be categorised in two main groups: wafer-type (single crystalline or multi-crystalline) and thin film. The former are made from wafers cut from a silicon ingot. Thin-film PV cells are deposited directly onto a substrate like glass, plastic or steel. Of the 1998 commercial PV market some 85% were wafer-type, while the remaining 15% were mainly amorphous silicon (thin film) solar cells (WEA, 2000). Other thin-film technologies are being developed in the laboratory, are in a pilot production phase, or are beginning to emerge as commercial technologies. Among the latter are notably CIGS (copper–indium/gallium–diselenide), CdTe (cadmium–telluride) and polymer-based solar cells. Today, it is too early to pick winners or losers among the PV technologies commercially available or under development. Still, there seems reasonable consensus that thin-film technologies offer the best long-term perspectives for low production costs, even when considerable cost reductions are to be expected for crystalline wafer technologies (resulting from technological improvements and economies-of-scale for these technologies). On the other hand, wafer-type silicon PV cells achieve today higher efficiencies (typically 12–15% for flat panels on the market) than those reached by thin-film technologies (around 6–11%), an empirical fact that might continue to hold for the longer-term future, even while efficiency improvements will probably be achieved for various technologies of each type such that efficiencies could be reached in the range of 20% in the medium term (up to 2020) and perhaps to some 30% in the long run (after 2020).[2] It seems likely that also in the future trade-offs will need to be made between cost and efficiency.

Table 1
Ranges of current and expected near-term capacity costs for four PV technologies (the ranges cover variations in supplier, type, size and country)

Capacity costs ($\$/W_p$)	Stand-alone PV system	Grid-connected PV system
Single crystalline silicon	5–30	3–8
Multi-crystalline silicon	5–30	3–8
Amorphous silicon	4–30	2–7
Other thin film	4–30	2–7

Sources: WEA (2000); Oliver and Jackson (2000).

PV system costs consist of module costs and costs of the so-called 'balance-of-system' (BOS), the latter representing all other system components, such as electrical installation, inverters, support structure and building integration. Prices of PV modules and systems vary widely, depending on supplier, type, size and country.[3] We therefore present merely cost *ranges*. For present and near-term crystalline silicon technologies, solar module costs vary between about 2 and 4 $\$/W_p$ (WEA, 2000).[4] For the corresponding BOS for rooftop and ground-based PV systems, when it is connected to the grid, costs vary between approximately 1 and 4 $\$/W_p$, so that the total system costs lie within a range of some 3–8 $\$/W_p$ (see Table 1).[5] For thin-film technologies, today's and short-term solar module costs can be expected to be around 1–3 $\$/W_p$, so that total system costs vary between 2 and 7 $\$/W_p$. For stand-alone systems, costs are significantly larger, e.g. as a result of additional battery and charge controller costs for energy storage. For representative present and near-term stand-alone PV systems, the costs one needs to add in this respect are readily 2 $\$/W_p$, but can be as much as 20 $\$/W_p$. Adding these figures to the costs already encountered with grid-connected PV systems, one arrives at present and near-term costs for stand-alone PV systems that lie in a range of about 5–30 $\$/W_p$ for

[2] These (conversion) efficiencies are the fraction of the incident solar radiation that is transformed into electricity.

[3] PV system *prices* (on commercial markets) are generally some 20–40% higher than PV system *costs* (of fabrication), since the former also reflect design and installation costs, as well as a profit margin. In the remainder of this paper, we will only consider PV (fabrication or manufacturing) *costs*.

[4] Costs in this paper are in principle expressed in $(2000), except when citing environmental damage costs estimated by the ExternE project: these are quoted in (but can be taken equal to the $ given the level of accuracy reached in our analysis).

[5] BOS costs are determined from BOS prices, while present BOS prices are derived from the difference between complete PV system prices (5–10 \$ per W_p) and PV module prices (3–6 \$ per W_p). The resulting present BOS costs (2–5 $\$/W_p$) are estimated to fall to 1–4 $\$/W_p$ in the near term.

Table 2
Electricity costs for four PV technologies, for the lower limit of the capacity cost ranges in Table 1, in relatively sunny climates (for which typically around 2.0 kWh per installed W_p is produced) and cloudy climates (typically characterised by 1.5 kWh/W_p

Electricity costs (¢/kWh)	Stand-alone		Grid-connected	
Annual output	2.0 kWh/W_p	1.5 kWh/W_p	2.0 kWh/W_p	1.5 kWh/W_p
Single crystalline silicon	22.7	30.3	13.6	18.2
Multi-crystalline silicon	22.7	30.3	13.6	18.2
Amorphous silicon	18.2	24.3	9.1	12.1
Other thin film	18.2	24.3	9.1	12.1

crystalline silicon, and about 4–30 $/$W_p$ for thin-film technologies (see also Table 1). Note that, because of the prevailing uncertainties, we have not distinguished between single- and multi-crystalline silicon technologies, and between amorphous silicon and other thin-film technologies, and that the upper range of 30 $/$W_p$ is very approximate.

The cost per kWh of PV electricity is obtained by dividing the annual cost of the system by its annual output. The total annual cost c_{ann}, including both capacity (capital investment) and operation and maintenance costs, is, according to the annuity relation for writing off investment capital:[6]

$$c_{ann} = C_{cap}\left(r_{O\&M} + \frac{r_{int}}{1 - (1 + r_{int})^{-N}}\right), \quad (1)$$

where C_{cap} is the capacity cost, $r_{O\&M}$ the annual cost of operation and maintenance (O&M, as percentage of C_{cap}), r_{int} the real interest rate (per year), and N the economic system lifetime (in years). We assume that $r_{O\&M} = 2\%$, $r_{int} = 5\%$, and $N = 25$ years.[7] Table 2 depicts the electricity costs of both stand-alone PV systems and grid-connected PV systems, in relatively sunny and cloudy climates (implying different annual electric outputs, expressed in kWh/W_p), obtained by assuming the lower values of capacity costs as displayed in Table 1 and by using Eq. (1).[8]

3. Costs of environmental damage

Low environmental damage is one of the main justifications for promoting solar energy, especially now that supply security has slipped from public consciousness. Since the EU has a stated goal of internalising the external costs of energy attributable to environmental damage, one can expect PV to gain an advantage because of its low damage cost. It is therefore interesting to present a brief summary and comparison of the damage costs generated by the use of some major energy technologies.

In recent years there has been much progress in the analysis of environmental damages, in particular thanks to the ExternE (External costs of Energy) Project series of the European Commission (ExternE, 1995, 1998, 2000). The damage cost estimates in these various publications are not always the same because the details of methodology have been evolving. The results published in 1995 are very similar to analogous studies in the USA (ORNL/RFF, 1994; Rowe et al., 1995), but the latter have not been updated during recent years. Here we use the numbers of Rabl and Spadaro, 2001, shown in Table 3; they are typical results for power plants, based on ExternE (1998).

The damage costs of ExternE (2000) for particulate matter (PM), nitrate aerosols and sulphate aerosols are about 0.6 times those of ExternE (1998), because of more conservative assumptions about the interpretation of epidemiological studies. For global warming the damage costs of ExternE (2000) are about 0.08 times those of ExternE (1998), because of different assumptions about the monetary valuation of damage costs and because an attempt has been made to also account for the benefits of global warming, such as increased agricultural production in northern countries.[9] Being sceptical of the more recent numbers, however, we continue to cite the larger numbers published in 1998. For global warming there is another reason for considering the higher number. The EU and most other industrialised countries have committed themselves to the Kyoto protocol. The cost of its implementation is

[6] The capital investment part of this relation is similar to that used to determine annually equal amounts to pay off, e.g. mortgages. Its straightforward derivation can be found in most standard references on finance and economics.

[7] An economic system lifetime of 25 years is, especially for stand-alone systems, assumed to be at the high side of what is technically feasible.

[8] As with capacity and electricity cost differences resulting from variations in a number of relevant factors as shown in Tables 1 and 2, differences may occur as a result of whether PV systems are installed in a centralised or distributed composition. These are not further analysed here.

[9] The difference between the ExternE (1998) and ExternE (2000) results constitutes a good example demonstrating how large the interval can be over which damage cost calculations may range (as a result of e.g. the specific technologies considered or technological assumptions made). This should be kept in mind when interpreting the results reported below that compare cost gaps with avoided damages.

Table 3
Typical damage costs per kg of pollutant emitted by power plants in Europe

Pollutant	Impact	Cost (€/kg)[a]
PM_{10}[b] (primary)	Mortality[d] and morbidity[e]	15.4
SO_2 (primary)	Crops, materials	0.3
SO_2 (primary)	Mortality and morbidity	0.3
SO_2 (via sulfates)	Mortality and morbidity	9.95
NO_2 (primary)	Mortality and morbidity	Small
NO_2 (via nitrates)	Mortality and morbidity	14.5
NO_2 (via O_3)	Crops	0.35
NO_2 (via O_3)	Mortality and morbidity	1.15
VOC[c] (via O_3)	Crops	0.2
VOC (via O_3)	Mortality and morbidity	0.7
CO (primary)	Morbidity	0.002
CO_2	global warming	0.029

Source: Rabl and Spadaro (2001).

[a] Variation with site and stack conditions:

- No variation for CO_2;
- Weak variation for secondary pollutants: factor of $\approx$0.5–2.0;
- Strong variation for primary pollutants: factor of $\approx$0.5–5 for site,
- and $\approx$0.6–3 for stack conditions (up to 15 for ground level emissions in big city).

[b] Particulate matter with diameter below 10 μm.

[c] Volatile organic compounds.

[d] Premature deaths.

[e] Illness.

high. In Germany, for instance, it has been estimated at about 20€/tonne of avoided CO_2 (Fahl et al., 1999), probably with similar numbers for many other countries. Assuming 20 \$/tonne of avoided CO_2, while a typical current coal-fuelled power station emits about 800 g/kWh, boils down to an implementation cost of some 1.6¢/kWh. This implies that in Germany the relevant avoided cost is this value rather than the real damage cost, whatever it may be. This value is much closer to the global warming damage cost as calculated in ExternE (1998) than the one determined in ExternE (2000).

3.1. Methodology

To evaluate the impact and damage cost of a pollutant, one needs to carry out an impact pathway analysis, tracing the passage of the pollutant from the place where it is emitted to the affected receptors (population, agricultural crops, buildings, etc.). This involves the use of dispersion models for both the local and the regional range (the European continent for the results cited here). For greenhouse gases the impact region covers the entire globe. Dose–response functions are used to calculate the impacts generated due to an increase in exposure, followed by a monetary valuation of these impacts. The entire fuel chain (or fuel cycle) is evaluated and compared on the basis of delivered end-use energy. For the fossil-fuel chain most of the damage costs arise from fuel combustion in power plants. For nuclear and renewable energy (with the exception of biomass combustion), by contrast, most of the impacts arise upstream and downstream from the power generation.

3.2. Damage cost per kg of pollutant

Damage costs per kg of pollutant for typical power plant emissions under European conditions are presented in Table 3. Some indication of the variability with site and stack conditions (exhaust height, exhaust temperature, exhaust velocity) is given in the notes under the table.

3.3. Results for fuel chains

Multiplying the cost per kg of pollutant by the emission rates as depicted in Table 4, one readily finds the pollutant cost per kWh of electricity. However, we warn against the temptation to cite cost/kWh numbers out of context, for instance as "the damage costs of coal". The damage costs of different coal technologies can vary very substantially, up to differences as large as an order of magnitude. Quite apart from the variation of impacts with the given technology, as well as the site of an installation, the very term "fuel chain" is also misleading, because it suggests a simple monolithic system while the reality is a chain whose elements can consist of a variety of different processes and technologies at different sites, emitting very different rates of pollution. Furthermore, thanks to ever more stringent environmental regulations, there has been a continual reduction of specific emissions (in the EU by a factor of 3–10 during the past decade, except for CO_2, for which reductions have been smaller). To illustrate this point we

Table 4
Emission of air pollutants for typical European fossil power plants

Emissions (g/kWh)	PM_{10}	SO_2	NO_x	CO_{2equiv}[b]
Coal, current	0.15	6	3	940
Coal, new	0.06	0.30	0.50	940
Oil, current	0.15	6	1.4	620
Oil, new	0.07	0.40	0.60	620
Gas comb.cycle, current	Negligible	Small[a]	1.1	430
Gas comb.cycle, new	Negligible	Small[a]	0.2	430

"Current" corresponds to typical emissions of existing fossil plants in the USA and France in 1995; "new" refers to estimated emissions of large new power plants built in the EU since January 2000. Emissions per kWh from simple gas turbines, often the main competition for PV because used for peak loads, are almost twice as high because of the lower efficiency.

[a] SO_2 emissions depend on composition of natural gas; in most cases it is negligible.

[b] CO_{2equiv} includes CH_4 and emissions from upstream activities of fuel chain.

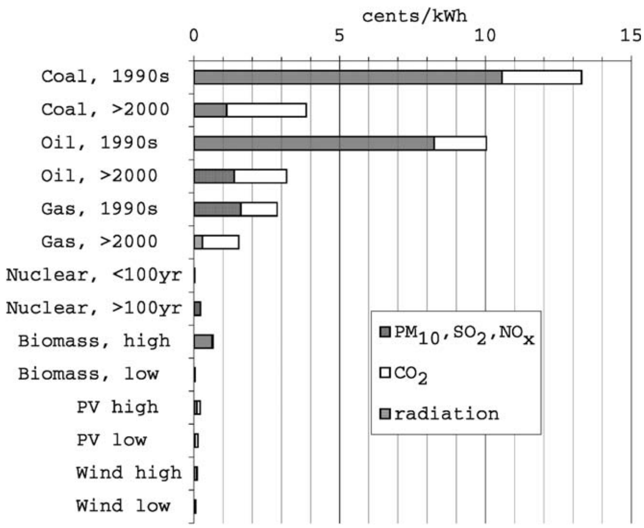

Fig. 1. Comparison of damage costs, for fuel chains in the EU, with costs (€/kg) of Table 3 and emissions (g/kWh) of Table 4. "High" and "low" for renewables indicate the typical range of estimates of ExternE (1998). For nuclear only a single technology is shown (French, with reprocessing), but costs are separated into near term and far future. Damage costs for hydro are extremely variable from site to site, but generally comparable to other renewables. For comparison, production cost of base load electricity in EU and USA is around 2–4 ¢/kWh.

list in Table 4 the measured emissions of PM_{10}, SO_2 and NO_x, for typical fossil plants in the USA and France during the 1990s, as well as estimated emissions for large new plants built in the EU after January 2000.

The damage costs are plotted in Fig. 1, showing separately the costs due to the classical air pollutants (PM_{10}, NO_x and SO_2), due to global warming (including upstream emissions of CO_2 and CH_4, expressed as CO_2 equivalent), and due to radionuclides (for nuclear energy). It is interesting to note that the damage costs for existing oil and coal fired power plants are very large, larger than the current production costs of electricity, of about 2–4 ¢/kWh, but that for newly built plants the damage costs of these two options have a value comparable to production costs.

The number for nuclear energy is based on the current technology used in France, including reprocessing (ExternE, 1995). It comprises the impacts over the entire globe and a time horizon of 100,000 years. Assessments for other countries have found roughly comparable results (ORNL/RFF, 1994; Rowe et al., 1995; ExternE, 1998). The damage costs for nuclear energy correspond to a zero effective discount rate (which equals the discount rate minus the escalation rate of costs). Because of the uncertainties and controversies surrounding intergenerational discounting, we show separately the costs imposed in the near term (first 100 years) and in the far future (beyond 100 years). For nuclear energy, the numbers cover all stages of the fuel cycle, including waste disposal, as well as major accidents. Still, any estimate of the latter two items remains controversial.

Even though the uncertainties are large (Rabl and Spadaro, 1999), the results provide substantial evidence that the classical air pollutants (particles, NO_x and SO_x) from fossil fuels impose a heavy toll, in addition to the costs of global warming. The damage costs are especially large for coal. Even with new technologies the damage costs for coal may be comparable to the price of electricity. For natural gas, the damage costs are about a third to a half of those for coal. The damage costs of nuclear power are small (at most a few %) compared to the price of electricity, and so are the damage costs of most renewable energy systems. If damage costs were internalised, the results in Fig. 1 imply that PV would gain a cost advantage of the order of 1–4 ¢/kWh relative to fossil fuels, and more so for older plants. With the increasing use of natural gas combined cycle plants, the lower range will probably be more relevant for the future, i.e. about 1 ¢/kWh. Even though PV without storage provides peak power and will often compete with simple gas turbines rather than combined cycle plants, with higher damage costs, we nevertheless use 1 ¢/kWh here because the other main competition for PV is hydropower (for which damage costs, although not indicated in Fig. 1, are estimated to be—apart from very variable—low in general).

With 1 ¢/kWh and an output of 1.5–2.0 kWh (W_p year) during 20–25 years, the damage cost avoided by PV is 0.3–0.5 $/$W_p$ if the discount rate is zero. Discounting at a social discount rate of about 5% (which we consider a reasonable value in this context) reduces this by a factor of about 0.6–0.7. Hence we assume that the credit for avoided damage costs amounts to about 0.25 $/$W_p$. Before using this number in the remainder of this article, we re-iterate that it is very much dependent on the technology used, the installation site, country and continent considered, the 'monetary value of life' used, and whether or not incorporating the 'willingness-to-pay' for emission reductions. Therefore, external costs remain a subject of large controversy. We will abstain from an extensive sensitivity analysis of our main results to the damage cost value used—the main subject matter of our study is the relevance of learning phenomena for PV. Our discussion in this section, however, on how to interpret damage costs and how to appreciate their variability, provides nevertheless a framework for evaluating the robustness of our findings in terms of our damage cost assumptions.

4. The prospect for cost reductions

Cost reductions for PV modules and systems can be evaluated in a number of ways. First, cost reductions can be evaluated through detailed technology assessments and analyses of manufacturing costs as a function of technological improvements (WEA, 2000). Through investigating cost reductions that correspond to likely technical innovations in various PV system components, one can estimate their future expected cost levels. Second, cost reductions can be assessed through what are called learning curves (IEA/OECD, 2000). With learning curves, the experience gained with a certain technology is expressed as a learning rate, that is, the percentage at which the unit cost decreases with every doubling of cumulative installed production. Learning curves are usually expressed as

$$c_t = c_0(n_t/n_0)^{\alpha}, \tag{2}$$

where c_t is the unit cost at time t, c_0 the unit cost at time 0, n_t the cumulative production at time t, n_0 the cumulative production at time 0, and α the learning elasticity parameter. With every doubling of cumulative production, costs decrease to a value expressed as the initial cost multiplied by a factor called the progress ratio pr (= 1—learning rate):

$$pr = 2^{\alpha}. \tag{3}$$

Costs that fall according to learning curves have been found for a wide range of industries, including energy production, and learning rates have been determined for them (see, for example, McDonald and Schrattenholzer, 2001). Data for PV module prices, for the years 1976–1999, are shown in Fig. 2. By plotting these data on a double-logarithmic scale one can directly derive the learning rate from the slope of the graph.

Typical learning rates range from 10% to 30% (although values have been observed that fall outside this range). A learning rate of 20% (progress ratio of 0.80) is an often-used best estimate future cost reduction potential for a variety of (energy) technologies. Learning rates are based on historic data for technologies that emerged, were commercialised and matured in the past (Grübler et al., 1999). There are many examples of technologies, however, that did not achieve this evolution, but reached an early death in an immature stage of development—e.g. by losing out to competing technologies. It is important to recognise this (and is often not done enough among learning methodologists), since it implies that it is not guaranteed that the learning rates of PV observed so far will continue to be applicable for future cost evolutions, in our case for PV technologies. Still, since the progress of R&D continues unabated and a number of known future technological improvements exists, we think that for the case of PV there is reason to believe that the pace of cost reductions will continue, and that it is likely to occur through a learning curve.

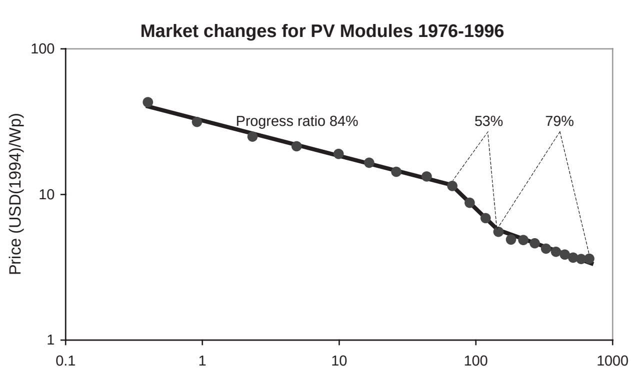

Fig. 2. Learning curve, with different sections, for PV modules between 1976 and 1996. The overall learning rate is about 20% (progress ratio of 0.80). Source: IEA/OECD, 2000.

Fig. 2 shows different learning rates for different sections of an example of a learning curve for PV. The overall learning rate determined from the depicted data, of about 20%, confirms earlier findings that PV module selling prices on the global market followed a learning rate of about 18% between 1976 and 1992 (Williams and Terzian, 1993), as well as results of a 20% learning rate observed on the Japanese market between 1981 and 1995 (Watanabe, 1999).

It is interesting to estimate how large a cumulative production n_b is needed to reach economic breakeven, defined as the point at which PV becomes competitive with conventional power plants. Let us take current PV systems costs of about 5 $/W$_p$, the average of the grid-connected values given in Table 1, and assume a financial breakeven cost of some 1.0 $/W$_p$. The latter value is chosen because calculations of costs per kWh (see Eq. (1)) show that capacity costs should be lowered to about this value, if the PV cells are installed in a sunny region, in order to arrive at currently competitive electricity prices (of around 4¢/kWh). Results are shown in Table 5, as a function of the progress ratio.

To put the numbers in perspective, we have also expressed them as percentage of the current world-wide power plant capacity of about 3300 GW (EIA, 2002). If the learning rate is higher than 20% (progress ratio lower than 0.80), the breakeven cumulative production n_b is at most a few per cent of this number, which may be acceptable. But should the future learning rate turn out lower, breakeven may remain elusive, because it would require an unrealistically large deployment at costs that are not competitive. Note that when the PV capacity is larger than roughly 20% of the total globally installed electric capacity, it must be designed as stand-alone systems, because a grid that is expected to be 'up' all the time cannot rely for a very high share on an intermittent energy resource as PV. With stand-alone systems, total electricity production costs become much higher.

Table 5
Effort required for reaching breakeven, in terms of cumulative production and cost gap, as function of the learning rate

Progress ratio, *pr*	0.7	0.75	0.8	0.85	0.9
Breakeven cumulative production, n_b (GW_p)	23	48	148	957	39700
Breakeven cumulative production, as % of 3300 GW, the present world capacity	0.7%	1.5%	4.5%	29.0%	1200%
Cost of reaching breakeven, C_b ($ billion)	37	74	211	1240	46800
Cost of producing $n_b - n_0$, if unit cost were already at breakeven, $(n_b - n_0)\ c_b$ ($ 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%

Source: authors' calculations. Assumptions: current cumulative production $n_0 = 1\,GW_p$, current unit cost $c_0 = 5$ $/$W_p$, breakeven unit cost $c_b = 1.0$ $/$W_p$.

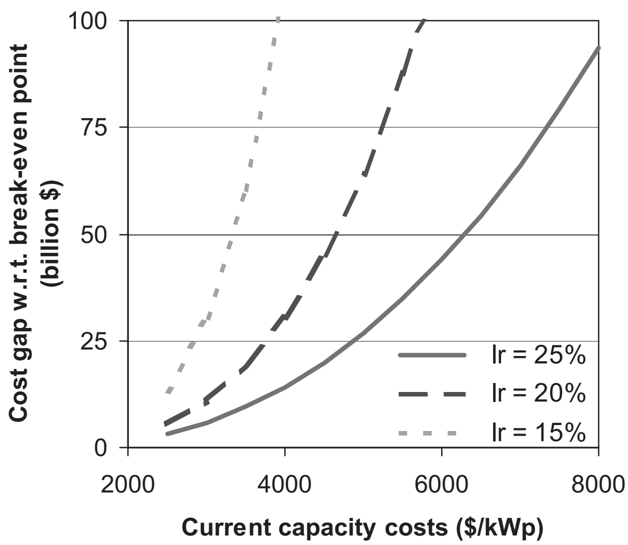

Fig. 3. The cost gap as a function of current unit cost, under different assumptions on the learning rate *lr*. Source: authors' calculations.

The cost of reaching breakeven, C_b, is readily calculated by integration under the learning curve:

$$\int_{n_0}^{n_b} c_n\,\mathrm{d}n = \frac{c_0}{\alpha+1}\frac{n_b^{\alpha+1} - n_0^{\alpha+1}}{n_0^{\alpha}}, \qquad (4)$$

in which c_0 is the present unit cost (5 $/$W_p$), α the parameter derived from Eq. (3) (*pr* being given in Table 5), and n_0 the current cumulative production (1 GW_p). The results are again shown in Table 5, together with the costs of producing $n_b - n_0$ if the unit cost were already at the breakeven level. The difference is the cost gap, i.e. the excess cost required to reach economic breakeven. For example, with a learning rate of 20% it is $64 billion of the $211 billion required to reach breakeven. The excess cost has to be paid by installations at places for which PV offers sufficient benefit compared to conventional technologies or by consumers who are willing to pay extra for cleaner electricity sources. If either of these is unavailable, various policy measures could be implemented to help to promote and deploy PV, as discussed in Section 5.

Given that current capacity costs can vary considerably, depending on location, type and manufacturer, we show in Fig. 3 how the cost gap varies as a function of the current capacity cost that is assumed, for several values of the learning rate. For central values of the relevant variables, the cost gap amounts to at least some $50 billion. Under less optimistic assumptions, the expected cost gap rapidly increases to levels beyond $ 100 billion.

5. Implications for energy policy

For PV technologies there is good reason to believe that the learning curve methodology provides an appropriate tool to assess future cost reductions.[10] Some of the main arguments are that

- PV is well beyond its initial introduction and is already commercialised in a wide range of energy applications;
- so far, PV cost decreases have been following rather well the learning curve model;
- PV has found sizable niche markets, where it is already competitive with current electricity alternatives;
- over the past two decades, the PV market has been expanding by some 15% annually and, recently, larger increases have been realised, which provides opportunities for cost reductions as a function of cumulative installed capacity; and
- cost reductions can be expected over the years to come from a technology assessment point of view (WEA, 2000) and from the continuing rapid pace of PV R&D.

[10] See, for example, the EU PHOTEX project that has as main purpose to analyse PV cost reductions through the development of learning curves for both complete PV systems and PV system components (EU, 2002).

Of course, the extrapolation from the past to the future remains uncertain. But our key results, shown in Table 5, include an immediate assessment of this uncertainty, because they are presented for a range of learning rates.

Of particular interest is the cost gap, i.e. the difference between the cost of the cumulative production before the breakeven point (at which PV can compete with currently available alternatives) and the cost of this production if instead an already competitive technology were used. The cost gap is large, in the order of 50 billion \$, and it could reach levels well above 100 billion \$. The ratio of the breakeven capacity and the currently installed capacity (of about one GW_p) is about 150, when the cost gap is assumed to be some 50 billion \$, and amounts to many hundreds, when a 100 billion \$ cost gap is expected.

Comparing cost gap and current annual PV sales, one sees that at the current global PV investment rate over two decades are required to reach the breakeven point in the former (optimistic) base case, while annual investments should be tripled if the breakeven point is to be reached within the coming two decades in the latter (less optimistic) case.[11]

Will the cost gap be overcome or will PV remain a technology limited to niche markets? If the natural dynamics of the evolution of the PV market are not sufficient, various policy measures in support of the technology may be needed to overcome the cost gap. Government subsidies are an example, although experience shows that subsidies are problematic: they tend to distort the market, and lobbying groups make them difficult to remove when they are no longer justified. A more promising approach, that can achieve the same objective, would be to require utility companies to have a specified minimum percentage of PV in their generating mix; the extra cost would be passed on to consumers. From the perspective of society, the cost of such a measure could be as large as the damage costs that are avoided when PV replaces conventional power plants.

Can such policy measures be justified by the environmental and health benefits of PV? The last two lines of Table 5 provide an answer to this question by showing that with a progress ratio of 0.8 the damage avoided by PV before breakeven would be \$37 billion compared to a cost gap of \$64 billion. Hence, the benefits would cover more than half of the cost gap. Note that two additional advantages of PV, enhancement of energy supply security and diversification of the energy technology mix, are not quantified and included here, but give additional rationale for justifying policy measures that stimulate PV deployment.

If damage costs were internalised, PV would gain a cost advantage in the order of 1 ¢/kWh, or 0.25 $\$/W_p$, relative to new fossil-fuelled plants, and more so for older fossil-fuelled plants. This is only 5% of the starting cost of $\$5/W_p$ that we assumed in Table 5. The reason why even with such a small percentage the benefits can cover such a large fraction of the cost gap is that the latter includes only the extra cost above the assumed breakeven cost of $\$1/W_p$. Most of the cost gap arises not from the initial PV sales (small volume at high cost) but from the very large volume that has to be sold near the breakeven point when costs are only slightly above breakeven. Note that the *increasing* percentages of avoided damage in the last row of Table 5, while the progress ratio *increases* (learning rate *decreases*), may appear counter-intuitive. The reason is that with a decreasing learning rate, the point in time at which breakeven is reached lies further in the future, implying proportionally higher extra damage costs (that accumulative linearly in time) than increases in the cost gap that needs to be bridged (with a convex decreasing slope).

6. Conclusions

This article has given an overview of the cost and performance of PV, and addressed its potential for cost reductions over the first few decades of the 21st century. We have assessed cost reductions that could be expected according to the learning-curve methodology, as well as the investments needed to reach economic breakeven. We have also estimated how much PV could gain if external costs (resulting from environmental and health damages) of energy resources were fully internalised, for example via an energy tax. Key results are shown in Table 5.

Our analysis yields four main conclusions:

(1) Mainly due to its high costs, PV electricity before 2020 is unlikely to play a major role in global energy supply and carbon emission abatement. PV should nevertheless be included in long-term energy scenarios, since beyond 2020 its contribution to electricity production could become significant, given its expected cost reductions and the general desire for reducing environmental damage and enhancing energy supply security thus limiting the dependence on (foreign) exhaustible non-renewable energy resources.
(2) Given its presumed learning potential, PV costs are likely to decrease significantly over the coming years, so that a considerable energy supply share from PV world-wide *could* materialise after 2020. The cost gap that still separates PV from reaching

[11] In recent years, some 300 MW_p PV has been installed annually world-wide. Supposing an average cost (grid and non-grid connected) of about 6 $\$/W_p$, one arrives at an annual global investment in PV of close to 2 billion \$.

breakeven with conventional technologies could be bridged during this time frame.

(3) If niche-markets, such as stand-alone applications in remote areas or in consumer goods, are not sufficient for bridging the cost gap, policy measures to encourage the construction of grid-connected PV systems are probably required to realise a long-term large-scale deployment of PV. Such policy measures could be justified in significant part, although probably not entirely, by the avoided damage costs that PV utilisation would imply. Additional justification comes from supply security. However, to our knowledge no estimates exist of the (monetary or political) value of the supply security that PV could bring.

(4) Damage costs (external costs) due to pollution emitted by conventional power sources are considerable, especially for older fossil-fuelled power plants, and their internalisation, e.g. by a pollution tax, would improve the competitiveness of PV, although probably not enough to close the current cost gap.

Above, we have explained why we think that the opportunities for PV are large and increased investments in this renewable energy source are most likely justified. By describing what share of the cost gap could be covered by avoided damage costs during the period in which breakeven is reached, we restricted our analysis to this limited time lapse only. It should be emphasized, however, that stretching one's view to after the breakeven point, it becomes clear that, from that point onwards, an energy alternative is available that for competitive costs does not involve the generation of negative environmental externalities, obviating for ever after the use of an environmentally detrimental (and thus more costly) conventional (fossil) alternative. This observation adds, in a long-term perspective, much to our conservatism employed so far.

A few critical notes should still be made. First, however attractive the learning curve methodology may seem, especially in that it allows for a rather straightforward analysis of cost reductions for large ranges of technologies, one of its major flaws remains, in the eyes of the authors, that it provides little to no explanatory value. This property of the learning methodology implies that it remains difficult to assess *how* precisely one needs to go about promoting PV or stimulating its cost reductions. It will be worthwhile to dedicate future research to the precise origins of what the reasons are that one perceives cost reductions to occur according to learning curves. Second, it is not obvious *where* niche markets exist for PV. We think, however, that detailed market and application investigations can shed light on this, and we therefore encourage future analysis in the nature of such niche markets, as well as in the particular size of it in the case of PV.

Finally, the high investments currently required to render PV competitive could well turn out, in the long run, to result in an overall social saving. The question remains, however, whether these investments should thus now be supported extensively, and if so, whether this support should be materialised through, e.g., energy taxes, tax exemptions, renewable subsidies, or other regulations. As for the former question, certain choices now could imply commitments, or technological lock-ins, for the future (for example, new technologies might be developed that prove superior to PV, rendering PV subsidy programs obsolete), so that large PV investments today should be carefully analysed before implementation. As for the latter question, precisely how to stimulate renewable energy sources is a subject of intricate expert discussion, which falls beyond the scope of this article. At any rate, since PV holds great promise and many desirable qualities, it deserves at least increased attention.

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