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Break-even Price Estimates for Residential PV Applications in OECD Countries with an Analysis of Prospective Cost Reductions

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This paper assesses the prospects for cost reductions of grid-connected photovoltaic (PV) systems to the estimated break-even price of $\$2.5/W_p$. At this price, PV technology could become cost-competitive without incentives for building-integrated applications in residential sectors of most industrialized countries. Significant reductions in the manufacturing costs of modules and inverters can be achieved by increasing production volumes or through technological innovation, e.g., by using less expensive materials. PV system costs can also be reduced by PV yield optimization, by increasing availability of a skilled labour force, and through design and construction innovations.

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INTRODUCTION

After commercialization began in the mid 1970's, PV systems have been characterized by high market growth rates and by a continuous trend of decreasing costs (or market prices). The indicator that is conventionally used to indicate progress in cost or price reduction for a given technology is the so-called progress ratio (PR), which is a measure of the relationship between the increase in the cumulative production and the decrease of unit costs (or prices). The PR quantifies the percentage cost declines for each doubling of cumulative production. Between 1989 and 2002, PV modules have been characterized by a PR of 80%, meaning that wholesale prices have decreased by 20 percent for every doubling of cumulative production (Poponi, 2003). At the end of 2002, cumulative shipments totaled about 2,380 MWp (MegaWatt-peak), while average wholesale prices of crystalline PV modules were about \$3/Wp (Maycock, 2002; 2003)1.

To date, market penetration of PV systems has depended upon the existence of niche markets (such as remote areas) and the institution of subsidies and tax credits. It is recognized that widespread commercialization of grid-connected PV systems will only occur if the market price of this technology decreases enough to make it a viable alternative to fossil fuels for electricity generation. In fact, the cost of electricity generated (CEG) from PV systems is substantially higher than the CEG from fossil fuel plants. The question to be addressed is whether PV technology could achieve the cost reductions necessary to reach the break-even price for a large market commercialization.

The two components that determine the total initial price of a grid-connected PV system are the modules (which account for at least 60% of the total price; see Table 1) and the Balance of Systems (BOS). The BOS includes different components such as mounting frames, power-conditioning equipment (e.g. the inverter), and site-specific installation hardware. Most of the reports that have analyzed the relationship between market growth and decreasing prices have focused on PV modules rather than PV systems. The main problem in calculating average costs for PV systems is the difficulty to obtain data on the BOS, given the heterogeneity of its components. The break-even price of PV modules, which is the price that can assure commercial viability without incentives or subsidies, has been estimated to be as low as \$0.5/W_p to values as high as \$1.2/W_p (International Energy Agency, 2000; Payne et al., 2001). However, the problem with some of the estimates published so far is the failure to recognise that there are different break-even prices for the different applications of PV systems, such as intermediate load

[1] Prices and costs are in US dollars.

generation in small PV power plants, peak-load generation in dispatchable systems, and building-integrated (BI) applications in customer-owned systems. The break-even price of PV systems depends on several parameters – including discount rate, tax treatment of depreciation, insolation, retail electricity price, etc. Findings from Byrne et al. (1997, 1998, and 2000) indicate that break-even prices are quite sensitive to the retail electricity price parameter (including monthly demand charges for connected loads of buildings (measured in kW) whereas they are much less sensitive to the insolation variable.

Table 1
Price distribution of residential PV systems in selected OECD countries, 2002

<table>
<tr><td rowspan="2">System size
Country</td><td colspan="2">2 kWp
Germany</td><td colspan="2">3 kWp
Italy</td><td colspan="2">3 kWp
USA (California)</td></tr>
<tr><td>$/kWp</td><td>%</td><td>$/kWp</td><td>%</td><td>$/kWp</td><td>%</td></tr>
<tr><td>modules</td><td>4700</td><td>68</td><td>5750</td><td>64</td><td>6000</td><td>60</td></tr>
<tr><td>inverter</td><td>750</td><td>11</td><td>1100</td><td>12</td><td rowspan="2">2500</td><td rowspan="2">25</td></tr>
<tr><td>mounting structure</td><td>600</td><td>9</td><td>900</td><td>10</td></tr>
<tr><td>installation labour</td><td>750</td><td>11</td><td>1000</td><td>11</td><td rowspan="2">1500</td><td rowspan="2">15</td></tr>
<tr><td>planning, documentation</td><td>100</td><td>1</td><td>250</td><td>3</td></tr>
<tr><td>TOTAL</td><td>6900</td><td>100</td><td>9000</td><td>100</td><td>10000</td><td>100</td></tr>
</table>

a) Used exchange rate 1$ = 0.87□
Scaheffer et al. (2004), IEA Photovoltaic Power Systems Programme (2004), Kahlon et al, (2003), Public Renewables Partnership (2004).

Building-integrated photovoltaic (BIPV) systems are the first market application where grid-connected photovoltaics could achieve market competitiveness (Byrne et al, 1997, 1998 and 2000; Poponi, 2003). This is due to the fact that, if net-metering is allowed, the CEG from the PV system will have to reach the level of the retail price of electricity, rather than the cost of electricity generated from the utility. In addition, in some industrialized countries (e.g. Italy, Denmark, Netherlands) the retail price of electricity is quite high (over $0.20/kWh) with respect to OECD average, a fact that strongly favors the market competitiveness of BIPV systems (Eurostat, 2003).

A sensitivity analysis of the break-even price of BIPV systems for households is carried out for different values of retail electricity prices and capacity factors (see Table 2), corresponding to selected OECD countries characterized by either high retail electricity prices or good insolation (or both, as is the case with Italy)[2]. The equation used in the sensitivity analysis is levelized electricity cost (LEC), in which initial capital cost (ICC) is

[2] Insolation data is given in terms of hours equivalent of full sunlight.

considered the unknown variable and LEC is set to the corresponding value of retail electricity prices, which is the target-cost of electricity generation from PV systems (see notes at the bottom of Table 2). The result of the sensitivity analysis in the residential sector is that break-even prices of BIPV systems range from $1.4/W$_p$ to $4.5/W$_p$. With the exception of Southern Italy, which is characterized by quite a favorable combination of retail electricity prices and solar radiation (and consequently the break-even price for PV systems is as high as 4.5$/W$_p$), most PV break-even prices for households within the OECD countries examined fall in the range between $2/Wp and $3/Wp. On the other hand, current retail prices of BIPV systems in grid-connected applications are in most OECD countries between $5/Wp and $8/Wp, depending on the national market and the total power of the system (IEA Photovoltaic Power Systems Programme, 2004; de Moor et al., 2004).

Assumptions on PV system lifetime and expected output, O&M costs and real discount rate are of particular importance in the sensitivity analysis. As far as the expected lifetime and the decline in generation of PV systems is concerned, the yield (expressed in kWh/kW$_p$) of PV plants in operation since the early 1980's has been recently monitored in several locations across the world, and after more than 20 years of operation only a small decrease in output (between 2 and 10% from the initial yield) was observed (Cereghetti, 2003; Thomas et al., 1999). Therefore, an expected lifetime of 25 years for PV systems could be considered a realistic objective if one takes into account a correct estimate of both ordinary and extraordinary O&M costs. In regards to the accuracy of the sensitivity analysis, it is assumed that the operation and maintenance costs (O&M) reflect both an ordinary component (the expenses for repairing the inverter and possible output losses) and an extraordinary one (the replacement of the inverter, assumed to take place at year 12 of operation). According to several estimates published in the literature (Thomas et al., 1999; Payne, 2001) ordinary O&M costs could range from $0.002/kWh to $0.01/kWh, but if we consider the evidence for recent improvements in inverter performance (IEA Photovoltaic Power Systems Programme, 2004), the level of $0.005/kWh could be considered as a possible estimate for PV systems to be commercialized in the next few years.

A very important assumption of the sensitivity analysis is that of a real discount rate set to a value of 5%. It could be argued that this value is too low, and, therefore, too optimistic for PV system potential buyers. However, it should be considered that the real discount rate normally reflects the opportunity cost of an alternative investment with the same degree of risk and revenue guaranteed for the expected PV system lifetime (assumed at 25 years). The risk associated with an investment on a PV system is very low, and only related to extraordinary maintenance costs, namely with the repair and replacement of the inverter. An alternative investment with a very low degree of risk, and in some cases (e.g. Italy) with revenues that can be guaranteed for more than 20 years, are Treasury Bonds with a long-term maturity. In most OECD countries the Internal Rate of Return (IRR) of these bonds does not exceed 5%.

It should be mentioned that comparing the LEC of PV systems with average retail prices might not be reasonable under all circumstances and would likely underestimate the value of PV electricity. One reason is that average residential electricity prices (which include the energy charge (kWh used), the taxes, and an estimate of demand charges) do not fully represent the economic benefits of BI photovoltaics. In fact, residential customers in the US, UK and in some EU countries pay a variable demand charge (peak kW measured by pulse meters) which in most cases would substantially increase the value of PV electricity and its competitiveness[3]. Other economic drivers of PV adoption are the benefits of avoided congested grids and transmission expansion investments, which should be correctly internalized in the tariff structure. Also, the benefits of pollution displacement should be taken into consideration, if we consider that in most of OECD countries the external costs of fossil-fuel electricity are not included in the tariffs of electricity. If environmental taxes and carbon emission permits are increasingly introduced, the competitiveness margin between fossil fuels and PV will be further reduced. Finally, non-economic drivers, such as the desire to be green of individuals and companies, have also played an important role in the diffusion of PV technology in recent years. For all these factors, the margin between the real cost of fossil-fuel electricity and the real value of PV electricity is substantially lower than the mere difference between the costs of electricity generated.

Below we address the question of whether there is enough potential for bringing PV system prices down to $2.5/$W_p$ - a level that can assure a widespread market commercialization in the residential sector of most industrialized countries. The goal of a $2.50/$W_p$ market price is considered by the PV industry an objective that can be realistically achieved during the next decade. For example, the US PV industry has recently released a 20-year roadmap that sets the objectives for the year 2020. These objectives are to increase production up to 6 GW_p per year and decrease PV module prices to $1.50/$W_p$. The Japanese roadmap for PV R&D and market implementation

3 In addition, because of the high retail electricity prices paid (particularly during the summer), commercial customers would also be likely to adopt BI photovoltaics in the future. Commercial buildings typically have expensive facade materials such as marble or stone, which makes BIPV systems cost-effective at $4-$5/Wp. In the commercial sector, dispatchable BIPV systems (systems with battery storage) are often more economical than non-dispatchable systems. This is due to the possibility of matching PV output with peak-load demand. See Byrne at al. (1997, 1998, and 2000)

considers an expected market price for residential PV systems of 300 Yen/W_p (about \$2.9/W_p at the current exchange rate) economically feasible by the beginning of the next decade. At this price PV systems would generate electricity at about 25 Yen/kWh, a level that would bring photovoltaics very close to market competitiveness against the electricity supplied by electric utilities (Jager-Waldau, 2002).

Table 2
Sensitivity analysis of break-even prices of BIPV systems for households in selected OECD countries [a]

Country	Location	Insolation (Heq) [b]	CF [c]	Retail electricity price[d] (\$/kWh)	Break-even price of PV systems (\$/Wp)
Portugal	Lisbon	5.20	0.173	0.1520	3.00
Spain	Madrid	5.00	0.167	0.1222	2.30
France	Marseille	5.00	0.167	0.1302	2.45
Italy	Palermo	5.20	0.173	0.2275	4.53
Greece	Athens	5.00	0.167	0.0752	1.38
Germany	Munich	3.60	0.120	0.1983	2.73
Netherlands	Amsterdam	3.20	0.120	0.2048	2.82
Denmark	Copenhagen	3.00	0.100	0.2837	2.92
USA	Los Angeles	5.80	0.193	0.1236	2.70
USA	New York	4.70	0.157	0.1370	2.43
Japan	Tokyo	3.70	0.123	0.2144	2.89

a) Break-even prices are calculated by using the formula for levelised electricity cost

$$LEC = (CCxCRF)/(CFx8760) + O\&M$$

Where LEC is the cost of electricity generated (\$/kWh), CC is the initial capital cost of the PV system (or the break-even price of PV systems, expressed in \$/KWh), CRF is the capital recovery factor, CF is the capacity factor, 8760 the number of hours/year, and O&M are the operation and maintenance costs. The CRF is defined by the formula $CRF = r + r/[1 + r)^n - 1]$. It is assumed that the lifetime of PV systems is 25 years, the real discount rate value used by residential PV users is 5% and ordinary O&M costs are \$0.005/kWh. It is also assumed that the inverter is replaced at year 12 of operation, resulting in a discounted cost of about 5% of the initial capital cost.

The sensitivity analysis of break-even prices is carried out for different retail electricity prices and capacity factor values. For example, with a real discount rate of 5% and a PV system life of 25 years, the resulting CRF is 0.07095. With a capacity factor of 0.173 and a target LEC of \$0.2275/kWh (the entry values for Italy), equation 1 becomes

$$0.1978 = (CCx0.07095x1.05)/(0.173x8760) + 0.005$$

which gives a CC of about \$4.53/Wp.

b) Insolation values are expressed in terns of hours equivalent of full sunlight (European Commission, 1984; NREL, 2004; IEA Photovoltaic Power Systems Programme, 2004).

c) Capacity factor values are obtained by assuming a 10% efficiency and a 20% output loss with respect to the maximum theoretical output. This loss is due to inverter efficiency and the fact that PV modules most of the time do not operate at Standard Test Conditions.

d) Used exchange rate: 1USD – 0.87□ (Eurostat, 2003; Energy Information Administration, 2004; IEA Photovoltaic Power Systems Programme, 2004).

Whether these goals will be achieved depends on different factors, factors that can be divided into the following categories. The first category of factors is related to the policy framework and economic context, such as the availability of incentives and subsidies and the existence of a sustained market demand. The second category of factors, which is the object of this paper, concerns the three phases of A) production of modules and other components by PV industries, B) assembly and installation, and C) operation and maintenance of PV systems. This paper analyzes and discusses in detail whether in these areas there is enough potential to substantially reduce the costs of PV systems.

1. REDUCING THE MANUFACTURING COSTS OF MODULES AND INVERTERS

The biggest potential for reducing PV system costs is in those components that are the result of manufacturing activities, such as modules and power conditioning equipment. In fact, module and inverter costs can range between 70 to 85 percent of total PV system costs (IEA Photovoltaic Power Systems Programme, 2004; Schaeffer et al., 2004).

Reductions in manufacturing costs can be determined by two factors: a) increases in production volumes; and b) technological innovations in the production process. A reduction in manufacturing costs leading to a lower market price of PV systems (for example achieved through an innovation in the manufacturing process) is likely to significantly boost the market demand for PV technology. As demand increases, the PV industry will increase the production capacity of manufacturing plants, and further economies of scale will be achieved, which could in turn provide additional opportunities for cost reductions.

1.1 Potential of Economies of Scale for PV Module Cost Reductions

An increase in annual production capacity and effective output of manufacturing plants can determine substantial reductions in production costs. Economies of scale can be achieved with the construction of manufacturing plants with higher output capacities that would allow a reduction in the amount of overhead costs per unit produced. Other important advantages that can be achieved by enlarging the scale of production are: a) a more efficient use of production equipment, since the production machinery is used more intensively and in a more optimal way. An additional advantage is the possibility of increasing and optimizing the throughput time of the production process. Production can also be improved with the deployment of newer, more efficient processes and extensive automation; b) the possibility of better coordinating and optimizing the ratio among the different factors of production (e.g. direct personnel and overhead factors). Furthermore, the cost of debt relative to the investment in the production plant can also be expected to decrease with a larger scale of production; and c) technological innovations can be used on a bigger scale (which could in turn amplify their impact on the production process). Additionally, the benefits of these innovations are greater with large-scale production lines (KPMG, 1999).

This potential of cutting production costs via economies of scale seems quite realistic, considering the likelihood that the PV industry will continue to build plants with higher annual production capacities as the market continues to grow exponentially. A specific example of how economies of scale work in production lines can be given with thin-film PV producing plants. According to the British Photovoltaic Association, scaling up PV thin-film factories from 10 to 100 MW_p/yr of capacity will result in a 40% reduction in unit manufacturing costs (Payne et al., 2001). Thin-film manufacturing facilities might find a substantial potential to reduce production costs by exploiting system design opportunities related to PECVD (Plasma Enhanced Chemical Vapor Deposition) reactors. Since PECVD reactors are among the most expensive pieces of PV production equipment and also one of the factors limiting the output production rate , thin-film PV industries have focused their attention on the objective of optimizing the ratio cost/output of these reactors. According to the estimates from Stabinsky (Stabinsky quoted by Payne et al., 2001), a thin-film PV company could theoretically produce an output of 100 MWp/yr of PV modules and achieve substantial economies of scale by grouping four 25 MWp/year PECVD reactors together. Production line components, such as the equipment for substrate handling, laser scribing, module testing and encapsulation would also offer a big potential for economies of scale. As a result of these improvements, the capital cost per unit produced will decrease substantially (Payne et al., 2001).

If we consider that the average price of PV modules was around \$3.00/W_p in 2002 (Maycock, 2003), a reduction of 50% in production costs is necessary for PV modules to reach the estimated break-even price for building-integrated applications of \$1.5/W_p (provided that BOS costs decrease proportionally with modules). A study from Bruton et al. (1996) analyzed the potential for PV module cost reductions that can be achieved with large-scale producing plants. The findings of this study indicate that a manufacturing plant with an annual production capacity of 500 MW_p could determine a reduction of PV module prices to about €0.91/W_p, if the best available technologies are used (Bruton et al., 1997). This study concluded in 1997 that the production of PV modules on such a very large scale is possible and could be achieved in the short term, although this possibility was investigated only for crystalline silicon technologies. An annual production capacity of 500 MW_p for a single plant means more than a three-fold increase from the biggest manufacturing lines in operation at the end of 2002, a possibility that will require a gradual scale-up of the plant and both sustained market demand and substantial investments from the PV industry. Another study focused on very large scale production of thin film PV (Keshner, Arya 2004). They found that operation of a 2-3 GW production facility would lead to module prices of $\$1/W_p$ without significant breakthroughs and with conservative assumptions. This is a factor of 100 times larger than the largest thin film plant in operation at this time. Cost reduction results from design and operation of such a large scale plant including on-site manufacture of the glass substrates, massively redundant parallel processing, and extensive recycling of unused raw materials.

1.2 Cost Reduction Potential from Technological Innovation and Improvements in the Production Process of Modules and Inverters

Technological innovation and improvements in the production process offer several opportunities for reducing manufacturing costs of modules and inverters, such as: a) standardizing manufacturing equipment among different industries and within different plants of the same industries; b) increasing the efficiency and throughput of cell production processes; c) using low-cost materials in manufacturing processes; d) increasing the efficiency of solar cells and inverters; and e) creating less costly methods for packaging and integrating modules.

One of the most promising opportunities for cutting the cost of PV modules is the use of less expensive materials, particularly thin-film technologies. Among the most common materials used in thin-film cells are amorphous silicon, copper-indium-gallium-diselenide, and cadmium telluride (Luque, Hegedus, 2003). Other companies are introducing PV modules made with very thin layers of semi-crystalline Si deposited on glass (Yamamoto etal 2002, Green 2004), requiring only a small fraction of the expensive high purity form of silicon used in conventional wafer-based PV cells (Zweibel, 1999). In fact, the cost of silicon usually amounts to 40% to 60% of the cost of crystalline silicon PV modules. The semiconductor layers for these thin film technologies mentioned above are 100 times thinner than a Si wafer. The market commercialization of thin-film modules started later than crystalline silicon PV. Therefore, as any other industry in the early stage of development, the potential for cost reductions might still be large. A possible market penetration of thin-film modules might also have a positive effect on the price of crystalline modules. In fact, if thin-film modules gain market share, the manufacturers of crystalline silicon modules might be forced to pursue more aggressive strategies for cost-reduction in order to compete successfully on the market. It is worth noting that the ultimate cost of all three thin film technologies approaches $1/Wp in sufficiently large scale production, despite differences in raw materials and semiconductor processing between them (Keshner, Arya 2004).

Generally speaking, it is very difficult to estimate to what extent technological innovation could contribute to the further reduction of manufacturing costs in the future. Nevertheless, there is general consensus in the scientific community that further technological innovations are likely to occur, and that these innovations (e.g., the successful development of "third-generation" photovoltaic modules) will be a major driving factor for reducing manufacturing costs in the middle and long run.

The impact of technological innovations is now particularly important in increasing the reliability of inverters, which play a very important role in the PV system yield and the cost of the electricity generated. The reduction in costs and the increase in performance (both in terms of efficiency and reliability) of inverters have now become a top priority of the PV industry. In fact, it has been observed that the technological progress of inverters has been much slower than that of PV modules. With an estimated 25-year lifespan of a PV system, it can be assumed that the inverter will have to be replaced at least once, and the recurring costs for this component do significantly increase the LEC of PV systems.

However, recent market developments in Japan and Germany have shown both an increase in reliability and a decrease in prices of inverters (De Moor at al., 2004; IEA Photovoltaic Power Systems Programme, 2004). There is enough evidence to indicate that the performance of PV inverters has increased in the following components and characteristics that have shown some problems, such as: ability to maintain the connection to the grid, effectiveness of array peak power tracking algorithms, nuisance trips of circuit breakers, and failures of source circuit fuses.

2. OPPORTUNITIES FOR COST REDUCTIONS IN BIPV SYSTEMS

BIPV products, such as shingles and slates, offer a substantial potential for reducing the cost of PV installations. A consistent part of the economic potential of these products is related to the fact that they can substitute expensive construction materials used in buildings. If PV systems are integrated in buildings from the roof-manufacturing stage, then significant cost reductions can be expected in the BOS component.

Thin-film modules are considered more versatile than crystalline silicon modules for integration in buildings. Two of the most important aspects for increasing the market penetration of BIPV products are the improvement in mechanical and electrical integration with the building and a better specialization of installers.

3. POTENTIAL FOR REDUCTION IN DESIGN AND INSTALLATION COSTS

Design and construction innovations can provide a big potential for cost reductions, especially in the case of photovoltaic power systems for utility scale applications. Creative design and installation techniques can decrease costs by reducing piece parts, minimal site preparation, and the use of standards components (Thomas et al., 1999). For example, the 400 KW_p PV power plant constructed in California by Advanced Photovoltaic Systems (APS) achieved a relatively low initial cost through several interesting innovations that can still be considered as valid cost-reduction opportunities for future PV power plants (Matlin et al., 1994).

First, the APS plant benefited from a design that minimized weight structure. This system used 50% less steel than any other design realized under the same PVUSA program. Since the cost of steel is one of the major factors that push up the BOS cost, the initial capital cost was lowered by $\$9.40/m^2$ or $\$0.24/W_p$ with respect to other designs (Matlin et al., 1994). Another solution that reduced the cost was to maximize the amount of fabrication done off-site, since the work that is done off-site can provide cost savings of about 35%. In addition, substantial savings were also obtained by making the field electrical connections either with plug type connectors or by self- piecing connectors. As a result, the 19,200 module connections were done without the need to strip the wire or tighten terminal block screws.

As far as installation costs are concerned, recent data from the EU-Photex project and the IEA Photovoltaics Power Systems Programme indicate that these costs account, on average, for about 10% of the total cost of small residential BIPV systems (de Moor et al., 2004; IEA Photovoltaics Power System Programme, 2004). Generally speaking, the more skilled and experienced the installers are, the lower the installation costs. In fact, it has been observed that inexperienced installers can take more than twice to install a system with respect to experienced ones (Dunlop et al., 2001). If the PV market continues to grow, and if the installation of PV systems is progressively integrated into the building construction activities, it can be expected that a skilled and well-trained labor force will be increasingly available. As a result, substantial cost reductions will likely be observed in the costs of installation of PV systems.

CONCLUSION

The analysis has highlighted several opportunities by which PV system costs can be reduced. In the short run, economies of scale are likely to be the most important factor for cost reductions, while in the middle and long run, the contribution of technological innovations will be essential to further reduce manufacturing costs. Given the relatively initial stage of market commercialization of PV systems, it is not possible to forecast what will be the level to which the prices of PV technology could be reduced before they eventually level off.

Considering the large potential for cost reductions, there is enough evidence to conclude that in the medium term (10-20 years from now), grid-connected photovoltaics will be able to reach the break-even price for building-integrated applications in the residential sector of most OECD countries. It can be competitive without incentives, especially in areas with high retail electricity prices, provided there is adequate support for R&D activities and market diffusion at least until the break-even levels are achieved.

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