Duke, R. D. and Kammen, D. M. (2003) **“Energy for Development: Solar Home Systems in Africa and Global Carbon Emissions”, *Climate Change for Africa: Science, Technology, Policy and Capacity Building*, Pak Sum Low, editor (Kluwer Academic Publishers), pp. 250-266.**

Chapter
12

Energy for Development: Solar Home Systems in Africa and Global Carbon Emissions

Richard D. Duke[*] and Daniel M. Kammen[**]

[*] *Science, Technology and Public Policy (STEP) Programme, Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ 08544-1013, USA.*
[**] *Director, Renewable and Appropriate Energy Laboratory (RAEL); Professor, Goldman School of Public Policy, and Energy and Resources Group (ERG), 310 Barrows Hall, University of California, Berkeley, CA 94720-3050, USA.*

Key words: Renewables, market transformation, photovoltaics, solar home systems, buydown, Clean Development Mechanism.

Abstract: A growing number of rural African households are using small solar home systems (SHSs) to obtain better access to lighting, television and radio. Various non-governmental organisations, multilateral institutions and international aid agencies have catalysed these markets, partially motivated by a desire to reduce global carbon emissions. This chapter assesses the carbon mitigation potential of African SHSs markets, concluding that direct carbon displacement will be limited. Indirect benefits from helping the global photovoltaics (PV) industry scale up production and bring down costs via the manufacturing experience curve will be larger, but still trivial relative to grid-connected markets. Nonetheless, with aggressive support, by 2025 SHSs could provide cost-effective basic electricity to a substantial share of rural households, and grid-connected PV could make a major contribution to overall electricity needs in Africa.

1. INTRODUCTION

The Kyoto Protocol under the United Nations Framework Convention on Climate Change (UNFCCC) allows for the creation of a Clean Development Mechanism (CDM). Under the CDM, so-called “Annex” countries that take on binding carbon abatement commitments may be able to partially comply by supporting initiatives that reduce greenhouse gas emissions in “non-Annex” countries. Solar home systems (SHSs) represent one possible arena for generating such trades of money and technology for abatement credits, and Africa is an important part of the current and potential market for SHSs.

A number of multilateral, national, private and non-governmental organisation (NGO) projects have already targeted SHSs in Africa. The World Bank Group’s Photovoltaic Market Transformation Initiative (PVMTI) has selected Kenya and Morocco for two of its three geographical focus areas. In addition, the Global Environment Facility (GEF) has recently completed a SHS project in Zimbabwe; it is currently implementing a SHS project in Uganda; and it is actively considering similar efforts in Benin, Cape Verde, and Togo (Kaufman *et al.*, 1999; Duke *et al.*, 2001). All of these are motivated in part by their carbon abatement potential.

Substantial NGO and private sector SHS efforts are also underway in South Africa. The government plans to rely heavily on SHSs for the next phase of its successful, but increasingly expensive, rural electrification programme – granting concessions to rent SHSs in defined rural areas to various businesses, including the South African utility ESKOM, Shell Solar, and the Dutch utility Nuon (Kammen, 1999; Anderson and Duke, 2001).

Even complete saturation of the global SHSs market would have a negligible direct impact on global carbon emissions. Nonetheless, the CDM, or any similar mechanism that ultimately emerges, might provide an important boost to SHSs markets. As detailed below, carbon abatement credits generated by SHSs could significantly reduce the price of solar electricity for rural households in developing countries.

In addition to direct abatement (primarily through displacement of kerosene lighting, battery charging, and to a lesser extent, generators), SHSs may also yield indirect carbon emissions reductions. First, SHSs are a near-term niche market for photovoltaics (PV). As such, SHS sales help to drive the virtuous cycle between (i) cost reductions from greater PV production experience; and (ii) increased global demand for PV due to those cost reductions (Duke and Kammen, 1999a). As a result of these dynamic effects, the African SHS market itself may marginally contribute to efforts to reduce the global price of PV – though major programmes to subsidise grid-connected residential and commercial markets in Japan, Germany, and other industrialised countries increasingly dominate global PV markets (Duke, 2002).

Another indirect carbon benefit associated with SHSs is that they may delay or displace conventional grid extension. There is no sure-fire technique for estimating the magnitude of this effect, but it appears to be operative in the South African context (Anderson and Duke, 2001).

These indirect market transformation and grid displacement benefits are unlikely to be sufficiently quantifiable to generate certified CDM credits, but they may motivate SHSs investments and support from public and private funders interested in promoting carbon abatement.

2. LEARNING AND EXPERIENCE CURVES

Learning curves describe the relationship between cumulative production of a manufactured good, such as PV, and the labour inputs necessary per unit produced.[1] During the 1970s, Boston Consulting Group (BCG) generalised the labour productivity learning curve to include all costs necessary to research, develop, produce and market a given product (Boston Consulting Group, 1972). That is, BCG argued that learning-by-doing occurs not only in the narrow sense of labour productivity improvements, but also in associated R&D, overhead, advertising and sales expenses.

These efficiency gains, in conjunction with the benefits from scale economies, often yield cost reductions characterised by an experience curve:

$$UC = a \bullet q^{-b}$$

Where *UC* = unit cost, *q* = cumulative production, *a* = the cost of the first unit produced, and *b* = the experience parameter.[2] The underlying intuition for this exponential relationship is that there are diminishing returns to experience. Cost reductions are fast initially, but taper off as worker productivity becomes optimised, production is fully scaled up, incremental process improvements are made, and so on.

Table 1. A taxonomy of learning-by-doing terms.

	Labor Costs Only	All Costs
No spillover	Firm-specific learning curve	Firm-specific experience curve
Perfect spillover	Industry learning curve	Industry experience curve

[1] This section draws from Duke and Kammen (1999a).

[2] See Hirschman (1964), Argote and Epple (1990), and Badiru (1992) for variants of the equation. Also, Arrow (1962) uses cumulative capital goods investment as the learning proxy.

In addition to distinguishing between learning and experience curves, it is also possible to apply this concept to individual firms or to an entire industry. Table 1 illustrates the four different possibilities. If a given firm is able to completely retain the knowledge that it generates from its own production experience, then a firm-specific learning or experience curve approach is appropriate. However, to the extent that learning-by-doing spills over among firms, an industry-wide approach is more applicable.

Spillovers are often substantial since firms routinely poach employees from each other, purchase equipment and other inputs from the same specialised suppliers, reverse-engineer their competitors' new products and even resort to industrial espionage. Lieberman (1987) discusses empirical evidence of spillovers as high as 60-90% in some cases and summarises other empirical literature suggesting high spillover rates.

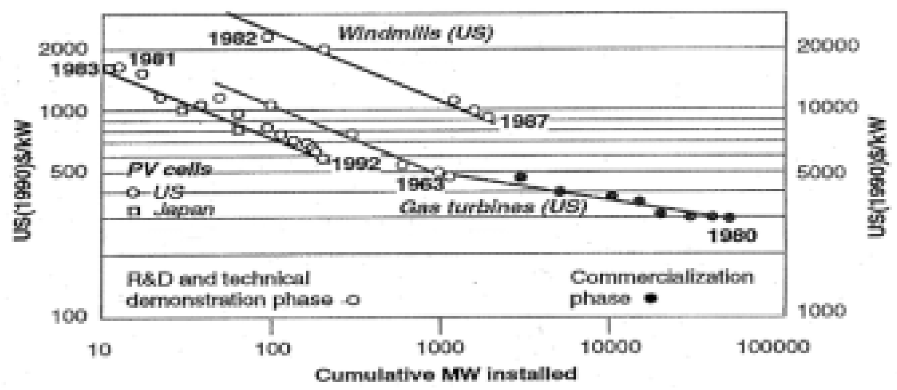


Figure 1. Industry-wide experience curve relationships for PV (right scale), wind generators (left scale), and gas turbines (left scale). (Source: IIASA/WEC, 1995).

The conventional measure of experience is the progress ratio (Dutton and Thomas 1984; Argote and Epple 1990). For each doubling of cumulative production, the cost per unit decreases by (1-PR) percent. **(what is this PR?)** Thus, counter-intuitively, higher progress ratios imply slower cost reductions.

Figure 1 illustrates experience curves for gas turbines, windmills and PV. The graph shows a tight relationship between cumulative industry-wide production and unit price, indicating that the industry experience curve is an appropriate approximation for PV. It is, however, important to highlight three concerns with this approach.

First, the experience curve for gas turbines is clearly "kinked" after 1963, underscoring that the slope of experience curves can change abruptly (in this case due to a transition from an active research and innovation phase to one dominated by deployment only). To account for this, we employ a range of progress ratio estimates in this analysis.

Second, unit price is an imperfect substitute for unit costs. Profit margins can and do vary, and this can be one reason for anomalies such as that observed for gas turbines (Boston Consulting Group, 1972). It is preferable to define learning and experience curves using manufacturing cost; however, where these data are unavailable, price provides a legitimate proxy if any of the following conditions hold (Lieberman, 1984):

1. Price/cost margins remain constant over time.
2. Price/cost margins change, but in a manner controlled for in the analysis.
3. Changes in margins are small relative to changes in production costs.

The third condition holds for PV since real module prices have fallen by a factor of 16 since 1975 (Johnson, 2002). Thus, short-term changes in the price/cost margin introduce only small deviations relative to the pronounced long-term cost reduction trend. Moreover, PV module production appears to be characterised by a high degree of innovation spillover, and this suggests that profit margins in the industry will tend towards a standard competitive rate of return (Duke, 2002).

Finally, there is reason to be concerned about the assumption that cumulative production experience is the sole determinant of unit costs. Hall and Howell (1985) argue that cost reductions are driven by five factors: (i) scale economies; (ii) technological progress; (iii) input price changes; (iv) internal efficiency improvements; and (v) learning-by-doing. Cumulative production unambiguously drives only the latter two factors, but Duke (2002) argues that intensive learning-by-doing is an essential prerequisite for scaling up both manufacturing and delivery mechanisms (e.g., marketing, regulatory interface, installation and maintenance) for energy technologies. There is also evidence that use-inspired process and technological innovations are major drivers of manufacturing cost reductions in a variety of industries (von Hippel, 1988), and Lieberman (1987) suggests that learning effects dominate economies of scale in driving cost reductions. Also, higher levels of cumulative production will tend to drive down key input prices (e.g., for specialised machinery) as suppliers gain production experience and take advantage of scale economies.

In sum, using cumulative production as the sole independent variable is a reasonable and parsimonious approach for the PV case. Moreover, Duke (2002) shows that adding variables for time or current production does not substantially improve the model, while Isoard and Soria (1997) survey multiple empirical analyses, showing that learning effects tend to dominate scale economies across multiple industries, including PV. Similarly, Watanabe (1999) performs an econometric analysis that suggests learning effects drive 70% of long-term price reductions in the Japanese PV industry.

3. USE OF EXPERIENCE CURVES FOR ANALYSING PV MARKETS

The Photovoltaic Market Transformation Initiative (PVMTI) is an initiative funded by the International Finance Corporation (IFC) and the GEF "…to significantly accelerate the commercialization, market penetration, and financial viability of PV technology in the developing world."[3] Project documents do not provide any quantitative estimates of PVMTI's impact on module prices, but a background paper for PVMTI refers to a progress ratio of 0.80 for PV in order to project business-as-usual (BAU) scenario price trends (World Bank Group, 1996) based on an experience curve approach.

Experience curves have been widely applied to analyse PV markets in academic papers, including a number of publications by the authors of this chapter. Duke and Kammen (1999a) model the positive feedback between demand and experience effects in order to examine PVMTI - concluding that the programme is too small to substantially affect global PV module prices, but SHS subsidies are potentially cost-effective if implemented efficiently. Duke and Kammen (1999b) show that restricting PVMTI support to immature/high-potential thin-film PV technologies might increase benefit-cost ratios, but this strategy would be risky and politically difficult. Payne *et al.* (2001) employ experience curves as a "top-down" cross check on the article's **(which article?)** "bottom-up" assessment of the cost reductions from scaling up thin-film PV production levels by an order of magnitude. Finally, Duke (2002) considers learning-by-doing spillover as a novel economic rationale for government "buydowns" of clean energy technologies and quantifies an optimal global "demand-pull" PV subsidy scheme to compensate for this externality.

Other academic work that has employed experience curves to analyse PV include a benefit-cost assessment of PV commercialisation efforts (Williams and Terzian, 1993) and various discussions of PV experience curves (such as Cody and Tiedje 1997; and Neij, 1997). Moreover, policy analysts outside of academia have often employed experience curves to assess PV markets. Examples include a recent EPRI **(what is the full name of this?)** brief on thin-film PV (Peterson, 1997) and Maycock (1996).

We now turn to a general discussion of the carbon abatement potential of global SHSs before specifically considering the potential importance of African SHS markets for climate change policy.

[3] World Bank Group (1996). Note that PVMTI documentation refers to experience curve analysis to underscore the validity of this "demand-pull" approach.

4. IMPACT OF SHS SALES ON FUTURE PV PRICE: A STATIC EXPERIENCE CURVE ANALYSIS

It is possible to extrapolate from the historical PV experience curve in order to estimate future PV prices as a function of projected sales growth rates. If the experience relationship holds, faster sales growth will mean more rapid unit cost reductions as the industry "rides down" the experience curve more quickly. Given a progress ratio of 0.80 and a 2000 wholesale price of about $4.00 per Wp (Nitsch, 1998; Harmon, 2000; Johnson, 2002) and assuming 20% annual sales growth, then modules prices will be expected to fall to $1.25 per Wp by 2020.[4]

It is possible to estimate the impact of current and projected SHSs sales on future PV prices by subtracting current and projected SHSs sales from the overall PV market projections, then using the experience curve to estimate how much higher prices will be in each year if it is assumed that all of these SHSs sales cease.

Table 2. Base case projections of the impact of global SHSs sales on PV price.

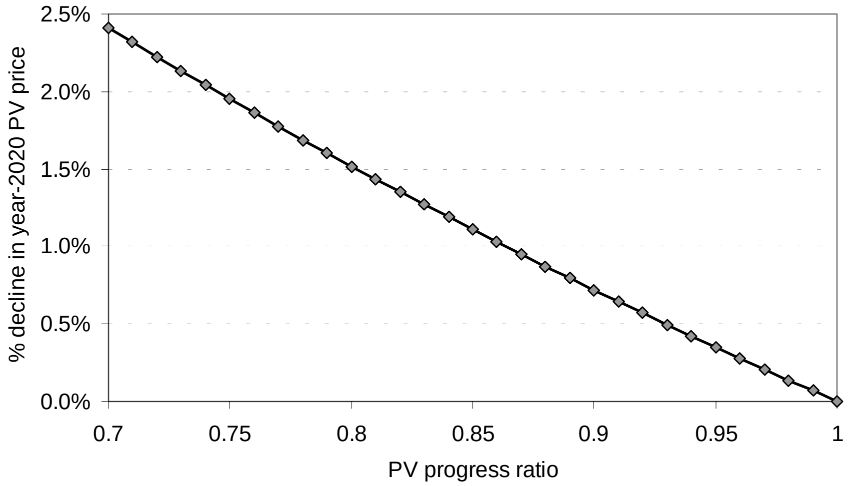
	No-SHS Scenario			SHS Scenario			
Year	Annual PV Sales in GWp	Cumulative GWp	$/Wp	Annual GWp SHS Sales	Cumulative GWp with SHS	$/Wp	Price Effect
2000	0.20	1.3	$4.00			$4.00	
2001	0.24	1.5	$3.78	.012	1.5	$3.77	0.3%
2002	0.29	1.8	$3.57	.014	1.8	$3.55	0.5%
2003	0.35	2.1	$3.37	.017	2.2	$3.35	0.7%
2004	0.41	2.5	$3.18	.021	2.6	$3.16	0.8%
2005	0.50	3.0	$3.01	.025	3.1	$2.98	0.9%
2006	0.60	3.6	$2.84	.030	3.8	$2.81	1.0%
2007	0.72	4.3	$2.68	.036	4.5	$2.65	1.1%
2008	0.86	5.2	$2.53	.043	5.4	$2.50	1.2%
2009	1.0	6.2	$2.38	.052	6.5	$2.35	1.3%
2010	1.2	7.5	$2.25	.062	7.8	$2.22	1.3%
2011	1.5	9.0	$2.12	.074	9.4	$2.09	1.3%
2012	1.8	11	$2.00	.089	11	$1.97	1.4%
2013	2.1	13	$1.89	.12	13	$1.86	1.4%
2014	2.6	15	$1.78	.13	16	$1.75	1.4%
2015	3.1	19	$1.68	.15	19	$1.65	1.5%
2016	3.7	22	$1.58	.19	23	$1.56	1.5%
2017	4.4	27	$1.49	.22	28	$1.47	1.5%
2018	5.3	32	$1.41	.27	34	$1.39	1.5%
2019	6.4	38	$1.33	.32	40	$1.31	1.5%
2020	7.7	46	$1.25	.38	48	$1.23	1.5%

World Bank Group (1998) estimates 1996 SHSs sales of 4-13 MWp. The base case for this analysis assumes 10 MWp for 2000, equivalent to 250,000 SHSs sold worldwide with an average size of 40 Wp. Assuming that SHSs sales match the projected 20% annual growth rate for the overall PV market, determining the projected impact of SHS sales on global PV module prices involves subtracting 12 MWp of SHSs sales from 2001, 14 MWp of projected SHSs sales from 2000, and so on. Under this thought experiment **(what is thought experiment?),** the estimated price of PV in 2020 is $1.23, or only 1.5% higher than the projection that includes SHSs sales.

[4] This analysis uses constant 2000 dollars and refers to wholesale module prices and sales volumes for the combined market for both crystalline and amorphous thin-film panels.

In this base case forecast, SHSs penetrate 11% of the maximum projected SHS market by 2020.[5] The assumed upper bound of 20,000 MWp of SHSs comes from projecting that 400 million households remain unelectrified through 2020 (with population growth roughly keeping pace with grid extension) and each of these homes purchases a 50 Wp system.

Figure 2. Decline in year-2020 PV module prices attributable to SHS markets, assuming base case parameters but varying



the PV progress ratio.

The estimated impact of global SHS sales on PV module prices is sensitive to the assumed progress ratio. Figure 2 above shows the percent PV price decline attributable to SHSs over the period from 2000 to 2020. If the progress ratio were to prove as low as 0.7, then the model predicts SHSs sales would cause a price decline of 2.4% over this 20 year period. However, if the future PV progress ratio worsens, the impact of projected SHSs sales on PV prices in this static analysis falls proportionately.

Figure 3 below shows the negative relationship between the growth rate of non-SHS PV sales and the impact on module prices of the SHSs component of the PV market.

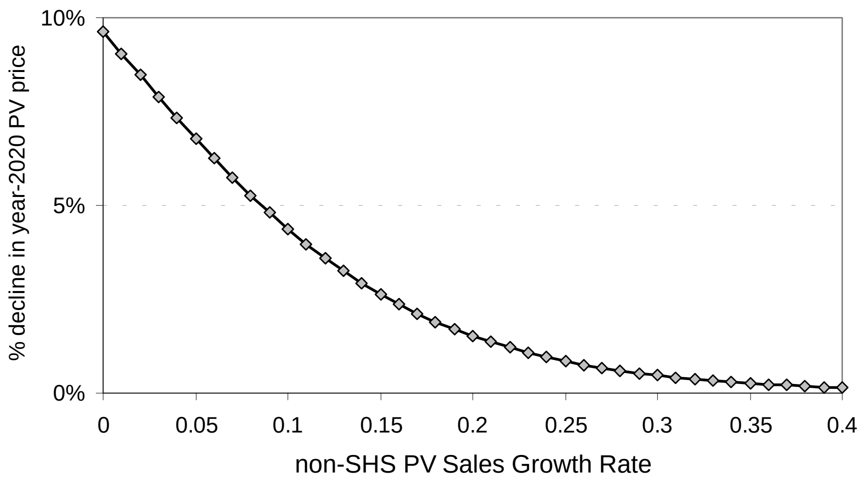
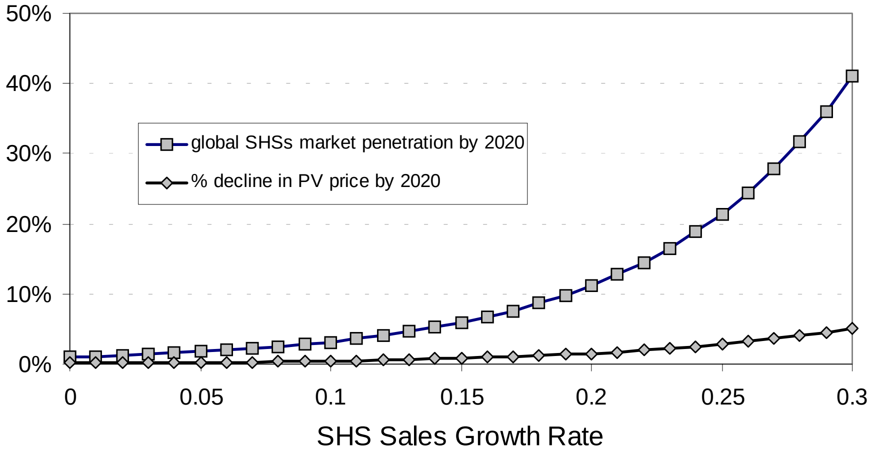


Figure 3. Decline in year-2020 PV module prices attributable to SHS markets assuming base case parameters but varying the non-SHS PV sales growth rate.

[5] It is important to note that this simple approach does not account for experience curve effects for balance of systems equipment, retail distribution, and installation, which collectively account for more than half of typical SHSs costs. It is likely that these costs would come down if the number of SHSs installed in any given country were to expand rapidly from a small initial base of cumulative experience. On the other hand, batteries are a mature technology and they represent about 30% of life cycle costs for standard 50 Wp **SHS systems (?)** (Banks, 1998) and up to 70% for small 10-20 Wp systems such as those typically found in Kenya (based on calculations derived from the lifecycle cost data in Duke *et al.*, 2000).

Figure 4 below shows that it is also possible to vary the projected SHSs sales growth rate. Holding the base case parameters constant, if annual SHSs increase at 30% rather than 20%, by 2020 this yields 40% saturation of the SHSs market and a price decline attributable to SHSs of about 6%.

Figure 4. Decline in year-2020 PV module prices attributable to SHS markets assuming base case parameters but varying the



SHS PV sales growth rate.

In sum, static analysis suggests that SHS markets are unlikely to play a major role in global PV commercialisation efforts. The next section discusses the implications of dynamic feedback mechanisms.

5. DYNAMIC CONSIDERATIONS

Two important factors driving the diffusion of any new technology are cost reductions through experience effects and the responsiveness of market demand to any such cost reductions. The latter can be characterised as the percent increase in sales associated with a 1% decline in price, i.e. the demand elasticity.

Anything that boosts PV sales will cause a price reduction via the experience curve. This, in turn, will induce an increase in future sales levels that will further reduce PV prices along the experience curve. This “virtuous cycle” will likely dampen over time (Colombier and Menanteau, 1997).

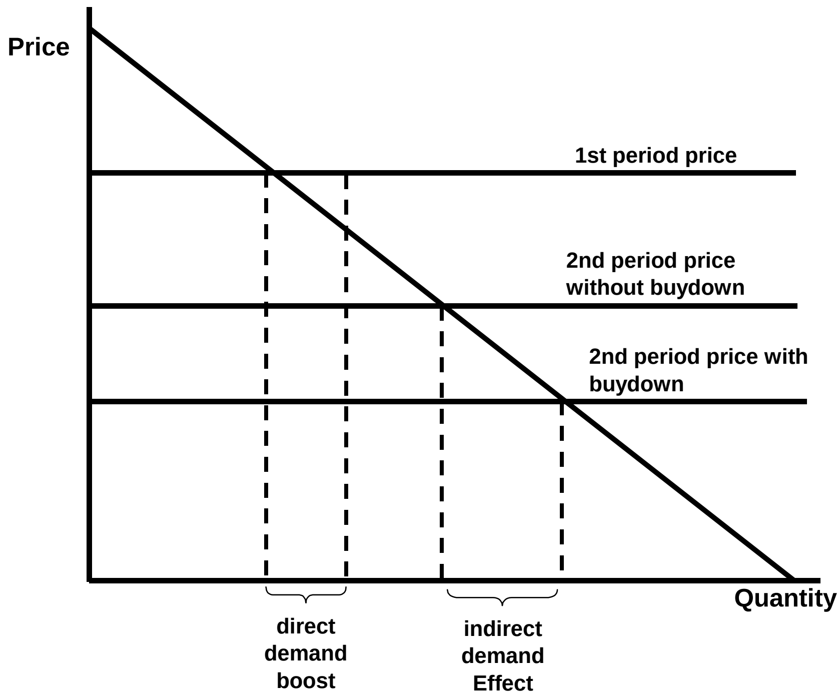


Figure 5. Two-period buydown.

Figure 5 presents a simplified two-period illustration of the positive feedback effect from a PV buydown. A one-period subsidy artificially inflates demand. As a result of associated experience benefits, in the second period unit cost is lower and the quantity of PV demanded is higher than it would have been absent the first-period buydown. In the third period this "indirect demand effect" drives prices down still further via the experience effect, and so on.

It is difficult to quantify the importance of these dynamic effects; however, one analysis suggests that the indirect demand effects of PVMTI may exceed the static benefits from the programme (Duke and Kammen, 1999a). Also, Duke (2002) develops methodologies for determining the optimal long-term subsidy path for demand-pull "buydown" programmes to help commercialise clean energy technologies like PV.

6. CARBON ABATEMENT IMPLICATIONS OF GLOBAL SHS MARKETS

It is important to assess the implications of the scenarios outlined above for CO_2 emissions. In the static base case, direct CO_2 displacement from SHSs is unlikely to have an important impact on global emissions. Even if the entire potential market of 400 million households receives SHSs, this would displace only approximately 20 million metric tons **(tonnes?)** of carbon equivalent (tC) annually, or about 0.3% of global emissions.[6]

Thousands of rural consumers purchase SHSs every year even though they receive no compensation for the value of avoided carbon emissions from kerosene lanterns. Forecasts of expected carbon prices range from about $15 to $350 per tC.[7] If carbon were to trade at $50/tC, this would amount to a lifetime carbon credit of about $50, for each 50 Wp panel – worth about one-quarter of current wholesale module prices. While hardly decisive, this would marginally boost the

[6] This assumes that each 50 Wp SHS displaces about 0.05 tC per year or about 1 tC over a 20-year system lifetime. These figures are based on an analysis of eight countries, taking into account kerosene lighting displacement as well as upstream emissions from fossil fuels, lead-acid battery production and PV module production (Ybema *et al*., 2000). Where data were available the authors also considered the secondary factors of emissions from candle usage and battery-charging stations.

[7] Energy Information Administration (1998) and White House (1998).

number and size of SHSs installed since the technology is already cost-effective in this application.[8] Of course, the CDM can play a useful role only if the transaction costs involved in certifying emissions reductions for SHSs are kept to an absolute minimum (Kaufman *et al.*, 1999).

In addition to direct carbon displacement, as noted every MWp of SHSs sold helps to lower the global market price for PV. As PV prices fall, sales in existing markets increases and new niche markets open up. For example, at present, residential grid-connected PV systems are not economic even in states with the most favourable combination of high insolation and expensive retail rates. If module costs fall to $1.50/Wp, then rooftop systems would become cost-effective in about one-tenth of new single-family homes constructed in the United States., or an annual market of about 500 MWp, i.e. twice the global level of PV module sales in 2000. At $1/Wp, the new home market increases by a factor of four and large residential PV retrofit markets also become viable (Duke *et al.*, forthcoming). Similar distributed grid PV markets exist globally.

As noted above, increased near-term SHSs sales could help to generate indirect demand effects in the global PV market. This substantially raises the carbon abatement value of SHS.

7. CARBON ABATEMENT IMPLICATIONS OF AFRICAN SHS MARKETS

As of 1999, there are approximately 770 million people in Africa, of which 630 million are in sub-Saharan Africa.[9] **[Can this figure be updated?]** Precise estimates are unavailable, but less than half of these people have access to grid electricity. That corresponds to a potential SHS market of 63 million households (out of a global total of approximately 330 million).[10] A 50% penetration rate with average system size growing to 50 Wp (as prices fall and rural incomes increase) translates into about 1,600 MWp of total PV demand, or six times global PV sales in the year 2000. **[So what was the actual figures in 2000?]**

There are, however, a number of unique aspects to the African SHSs market that must be considered. Most importantly, the majority of the rural population in Africa lives in extreme poverty. This means that substantial subsidies and aggressive measures to reduce the “first-cost” barrier are particularly important in the African context. The fee-for-service programmes emerging in South Africa are encouraging in this regard, but delays in disbursing promised subsidies threaten to undermine their impact (Anderson and Duke, 2001).

Moreover, especially in the South African context, there are important political issues related to SHSs dissemination. Rural South Africans generally view SHSs as a second-best option relative to heavily subsidised grid connections that would provide them with considerably better service for similar or lower monthly payments. As it proceeds with its SHS efforts, the government of South Africa must therefore balance fiscal constraints on increasingly expensive grid-based electrification with the risk of being perceived as perpetuating a history of second-class electricity service for black South Africans.[11]

8. RENEWABLES SCENARIOS FOR AFRICA

As of 1995, Africa derived 16% of its grid electricity from renewable sources, and hydropower accounted for over 99% of this total.[12] As of 2002, 50-125 MWp of off-grid PV had been installed in

[8] Note that the CDM would probably recognise carbon benefits only as they accrue. In that event, the stream of carbon abatement benefits from each SHS would have to be discounted. At a 5% real discount rate, this lowers the present value to about US$25.

[9] www.prb.org/pubs/wpds99/wpds99a.htm.

[10] Assumes an unelectrified African population of about 440 million in 2000 and an average rural household size of seven (derived from World Resources Institute, 1998).

[11] For further information, an on-line documentary produced by Anderson and Duke (2001) is viewable at [www.princeton.edu/duke].

[12] World Resources Institute (1998). Total primary energy includes all conventional energy as well as traditional fuels defined as various forms of animal and vegetable biomass.

Africa.[13] SHSs account for roughly one-third of this, with the remainder in telecommunications and various government and donor projects (e.g., water pumping, schools, and health clinics).[14] This is equivalent to just 0.03% of total grid electricity generated.

Projecting forward to the year 2025, if off-grid PV sales increase at 15% annually, then off-grid PV provides 0.8% of total expected grid electricity generation by 2025 based on 3 GWp of installed capacity.[15] This is an aggressive projection since it is equivalent to providing a 50 Wp SHS for all 60 million currently unelectrified African households. Electrification efforts have often failed to keep pace with population growth in rural Africa, however, and average system sizes should increase as SHS prices fall. Moreover, as off-grid markets begin to saturate, grid-connected PV could grow to become a major factor in African energy markets and some of the larger-scale companies involved with providing rural solar installations might transfer their expertise to grid-connected markets as they emerge.

In sum, PV has the potential to contribute to the African energy supply while providing critical development benefits to rural populations and improving both the local and global environment. Growth in SHS and subsequent grid-connected markets will likely prove modest, however, without sustained and aggressive public support. Assessing the available policy options, and the desirability of this goal relative to other public priorities, requires further analysis.

9. ACKNOWLEDGEMENTS

The authors wish to thank the anonymous reviewers for useful edits and suggestions.

10. REFERENCES

Abell, D.F. and Hammond, J.S. (1979) *Strategic Market Planning.* Englewood Cliffs: Prentice-Hall.

Anderson, J. and R. Duke (2001). Solar for the Powerless: Electrifying Rural Africa with the Sun (viewable at www.princeton.edu/duke).

Argote, L. and Epple, D. (1990) Learning curves in manufacturing, *Science* 247: 920-924.

Arrow, K.J. (1962) The economic implications of learning by doing. *Review of Economic Studies* 29: 166-170.

Badiru, A.B. (1992). Computational survey of univariate and multivariate learning curve models. *IEEE Transactions on Engineering and Management* 39 (2): 176-188.

Banks, D. (1998). Off-grid electrification for the poor: constraints and possibilities, Energy & Development Research Centre.

Boston Consulting Group, Inc. (1972) *Perspectives on Experience*. Boston: The Boston Consulting Group, Inc.

Cody, G.D. and Tiedje, T. (1997) A learning curve approach to projecting cost and performance for photovoltaic technologies. Presented to Future Generation of Photovoltaic Technologies NREL Conference held in Denver, Colorado, March 24-26.

Colombier, M. and Menanteau, P. (1997) From energy labelling to performance standards: some methods of stimulating technical change to obtain greater energy efficiency. *Energy Policy* 25 (4): 425-434.

Duke R., Williams, R.H. and Payne, A. (forthcoming). Accelerating residential PV expansion: Demand analysis for competitive electricity markets.

Duke, R. (2002). Clean Energy Technology Buydowns: Economic Theory, Analytic Tools, and the Photovoltaic Case, Ph.D. Dissertation, Princeton University.

Duke, R. D., Graham, S., Hankins, M., Jacobson, A., Kammen, D.M., Osawa, B., Pulver, S., and Walther E. (2000). Field Performance Evaluation of Amorphous Silicon (a-Si) Photovoltaic Systems in Kenya: Methods and Measurements in Support of a Sustainable Commercial Solar Energy Industry, World Bank.

[13] Maycock (1996) suggests that Africa accounted for 10-13% of the global PV market in 1995. Assuming 10% of the cumulative global sales of 0.5 GWp implies cumulative PV installations in Africa of about 50 MWp by 1995. Cumulative global PV sales reached about 2 GWp by the end of 2002 and roughly half of this was in off-grid installations (though the off-grid share has been diminishing rapidly as subsidised grid-connected markets in industrialised countries have taken off). Assuming Africa maintained a 10% share of off-grid sales, this would imply additional PV installations in Africa of as much as 75 MWp: (2 GWp – 0.5 GWp) * 50% off-grid * 10% Africa share.

[14] This assumes there will be about 150,000 SHSs averaging 25 Wp each in Kenya and another 500,000 SHSs scattered throughout the rest of Africa, with an average size of 40 Wp, yielding total SHS installations of 24 MWp. The Kenyan estimates are extrapolated from van der Plas and Hankins (1998).

[15] This assumes electricity consumption increases at 2% annually based on the GDP growth rate for Africa during 1990-1997 and total off-grid PV installations in Africa were about 16 MWp in 2002 (about 10% of the global off-grid PV market).

Duke, R. and Kammen, D.M. (1999a) The Economics of Energy Market Transformation Programs. *The Energy Journal* 20 (4): 15-64.

Duke, R. and Kammen, D.M. (1999b) PV Market Transformation: The virtuous circle between experience and demand and the strategic advantage of targeting thin-film photovoltaics. Presented at the IEA Workshop On Experience Curves For Policymaking –The Case Of Energy Technologies, Stuttgart, 10-11 May.

Duke, Richard. D, Jacobson, Arne, and Daniel M. Kammen (2001) Product quality in the Kenyan solar home industry. *Energy Policy*, 30 (6), 477-499.

Dutton, J.M. and Thomas, A. (1984) Treating progress functions as a managerial opportunity. *Academy of Management Review* 9 (2): 235-247.

Energy Information Administration (1998) *Impacts of the Kyoto Protocol on U.S. Energy Markets and Economic Activity.* (US Department of Energy, Washington, DC.

Hall, G. and Howell, S. (1985) The Experience Curve from the Economist's Perspective. *Strategic Management Journal*, 6: 197-212.

Harmon, C. (2000). Experience Curves of Photovoltaic Technology. Laxenburg, International Institute for Applied Systems Analysis.

Hirschman, W.B. (1964) Profit from the learning curve. *Harvard Business Review*, January-February, 125-139.

IIASA/WEC (1995) *Global Energy Perspectives to 2050 and Beyond.* (Laxenburg, Austria and London, UK).

Isoard, S. and A. Soria (2001). Technical change dynamics: evidence from the emerging renewable energy technologies. *Energy Economics* 23: 619-636.

Johnson, R. (2002). Personal communication.

Kammen, D. M. (1999) Bringing power to the people: Promoting appropriate energy technologies in the developing world. *Environment*, 41 (5), 10 – 15, 34 - 41.

Kaufman, S., Duke, R.D., Hansen, R., Rogers, J., Schwartz, R. and Trexler, M. (2000) *Rural Electrification with Solar Energy as a Climate Protection Strategy.* Renewable Energy Policy Project.

Lieberman, M.B. (1984) The learning curve pricing in the chemical industries. *Rand Journal of Economics* 15: 213-228.

Lieberman, M.B. (1987). The learning curve, diffusion, and competitive strategy. *Strategic Management Journal* 8: 441-452.

Marnay, C., Richey, R.C., Mahler, S.A. and Markel, R.J. (1997) *Estimating the environmental and economic effects of wide spread residential PV adoption using GIS and NEMS.* Lawrence Berkeley National Laboratory, LBNL-41030.

Maycock, P. (1996) *Photovoltaic technology, performance, cost and market forecast: 1975-2010.* PV Energy Systems, Inc.

Neij L. (1997) Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology. *Energy Policy* 25 (13): 1,099-1,107.

Nitsch, J. (1998). Probleme der Langfristkostenschätzung – Beispiel Regenerative Energien. Vortrag beim Workshop Energiesparen – Klimaschutz der sich rechnet, Rotenburg an der Fulda, 8-9 October.

Payne, A., Duke, R.D. and Williams, R.H. (2001) Accelerating Residential PV Expansion: Supply Analysis for Competitive Electricity Markets. *Energy Policy*. **???**

Peterson, T. (1997) *Making photovoltaics economical for electric utilities.* Electric Power Research Institute Strategic R&D Report, Fall.

UPVG (1994) *PV Vision.* The Utility Photovoltaics Group, 2(2).

Van der Plas, R.J. and Hankins, M. (1998) Solar electricity in Africa: a reality, *Energy Policy* 26 (4): 295-305.

Von Hippel, E. (1988) *The Sources of Innovation.* New York: Oxford University Press.

Watanabe, C. (1999). Industrial dynamism and the creation of a "virtuous cycle" between R&D, market growth and price reduction: The case of photovoltaic power generation (PV) in Japan. Experience Curves for Policy Making: the case of energy technologies. C.-O. Wene, A. VoB and T. Fired, IEA. *Proceedings of the IEA International Workshop at Stuttgart, Germany, 10-11 May, 1999.*

White House (1998) *The Kyoto Protocol and the President's Policies to Address Climate Change: Administration Economic Analysis.* (White House, Washington, DC: July 1998).

Williams, R. and Terzian, G. (1993) *A benefit/cost analysis of accelerated development of photovoltaic technology.* Princeton University Centre for Energy and Environmental Studies, Report No. 281.

World Bank Group (1996) *Photovoltaic Market Transformation Initiative Background Paper.* International Finance Corporation and World Bank Staff.

World Bank Group (1998) *Solar Development Corporation.* Project Brief, International Finance Corporation and World Bank Staff.

World Resources Institute (1998) *World Resources 1998-99.* Oxford University Press.

Ybema, J.R., Cloin, J., Nieuwenhout, F.D.J., Hunt, A.C., Kaufman, S.L. (2000) *Towards a Streamlined CMD Process for Solar Home Systems: Emission reductions from implemented systems and development of standardised baselines.* ECN-C-00-109, available for download at [http://www.ecn.nl/unit_bs/kyoto/mechanism/cdmshs.html].