15 Energy for development: solar home systems in Africa and global carbon emissions

RICHARD D. DUKE[1] and DANIEL M. KAMMEN[2]

[1]*Princeton University, USA,* [2]*University of California, Berkeley, USA*

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ABSTRACT A growing number of rural African households are using small solar home systems (SHS) to obtain better access to lighting, television and radio. Various non-governmental organizations, 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 SHS 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, by 2025 SHS could provide cost-effective basic electricity to a substantial share of rural households, and grid-connected PV could make an important contribution to overall electricity needs in Africa.

15.1 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 (SHS) 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 SHS.

A number of multilateral, national, private and non-governmental organization (NGO) projects have already targeted SHS 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 may rely heavily on SHS for the next phase of its successful (but increasingly expensive) rural electrification programme – granting concessions to rent SHS 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 SHS market would have a negligible direct impact on global carbon emissions. Nonetheless, the CDM, or similar mechanisms, might provide an important boost to SHS markets. As detailed below, carbon abatement credits generated by SHS 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), SHS may also yield indirect carbon emissions reductions. First, SHS 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

*Current address: McKinsey & Company, Florham Park, NJ, USA

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the global price of PV – though major programmes to subsidize grid-connected residential and commercial markets in Japan, Germany, and other industrialized countries increasingly dominate global PV markets (Duke, 2002).

Another indirect carbon benefit associated with SHS 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 SHS investments and support from public and private funders interested in promoting carbon abatement.

15.2 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) generalized 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 characterized by an experience curve:

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

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 optimized, production is fully scaled up, incremental process improvements are made, and so on.

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 15.1 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.

Table 15. *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

Spillovers are often substantial since firms routinely poach employees from each other, purchase equipment and other inputs from the same specialized 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 summarizes other empirical literature suggesting high spillover rates.

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 – progress ratio) per cent. Thus, counter-intuitively, higher progress ratios imply slower cost reductions.

Figure 15.1 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,

[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.

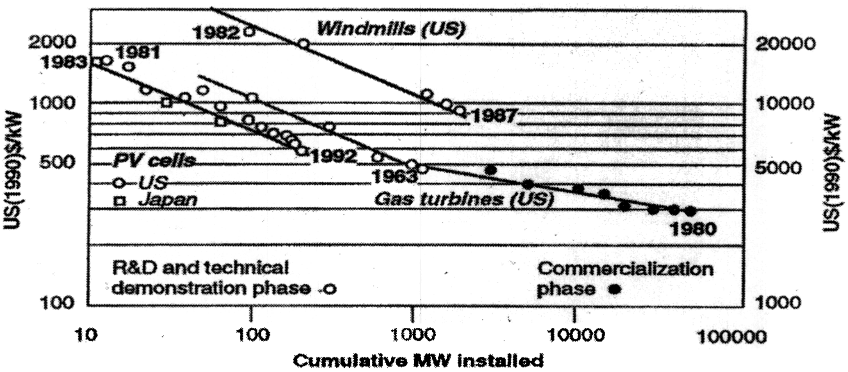

Figure 15.1. Industry-wide experience curve relationships for PV (right scale), wind generators (left scale), and gas turbines (left scale). (Source: IIASA/WEC, 1995).

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 characterized 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 specialized 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.

15.3 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 analyze 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 its '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.

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

Table 15.2. *Base case projections of the impact of global SHS 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					
2001	0.24	1.5		0.012	1.5		0.3%
2002	0.29	1.8		0.014	1.8		0.5%
2003	0.35	2.1		0.017	2.2		0.7%
2004	0.41	2.5		0.021	2.6		0.8%
2005	0.50	3.0		0.025	3.1		0.9%
2006	0.60	3.6		0.030	3.8		1.0%
2007	0.72	4.3		0.036	4.5		1.1%
2008	0.86	5.2		0.043	5.4		1.2%
2009	1.0	6.2		0.052	6.5		1.3%
2010	1.2	7.5		0.062	7.8		1.3%
2011	1.5	9.0		0.074	9.4		1.3%
2012	1.8	11		0.089	11		1.4%
2013	2.1	13		0.12	13		1.4%
2014	2.6	15		0.13	16		1.4%
2015	3.1	19		0.15	19		1.5%
2016	3.7	22		0.19	23		1.5%
2017	4.4	27		0.22	28		1.5%
2018	5.3	32		0.27	34		1.5%
2019	6.4	38		0.32	40		1.5%
2020	7.7	46		0.38	48		1.5%

Other academic work that has employed experience curves to analyse PV include a benefit-cost assessment of PV commercialization 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 Electric Power Research Institute (EPRI) brief on thin-film PV (Peterson, 1997) and Maycock (1996).

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

15.4 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 module prices will be expected to fall to $1.25 per Wp by 2020, based on cumulative sales of 48 peak gigawatts (GWp).[4]

It is possible to estimate the impact of current and projected SHS sales on future PV prices by subtracting current and projected SHS 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 SHS sales cease.

World Bank Group (1998) estimates 1996 SHS sales of 4–13 peak megawatts (MWp). The base case for this analysis assumes 10 MWp for 2000, equivalent to 250,000 SHS sold worldwide with an average size of 40 Wp. Assuming that SHS 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 SHS sales from 2001, 14 MWp of projected SHS sales from 2000, and so on. Removing SHS markets

[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.

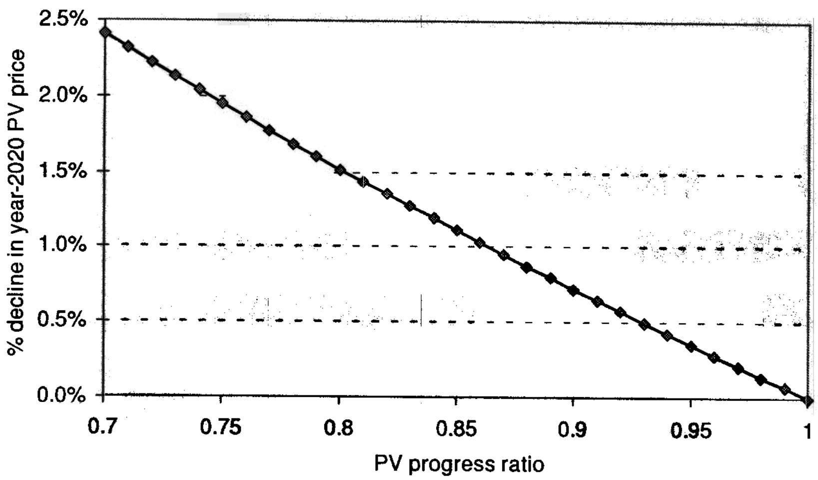

Figure 15.2. Decline in year-2020 PV module prices attributable to SHS markets, assuming base case parameters but varying the PV progress ratio.

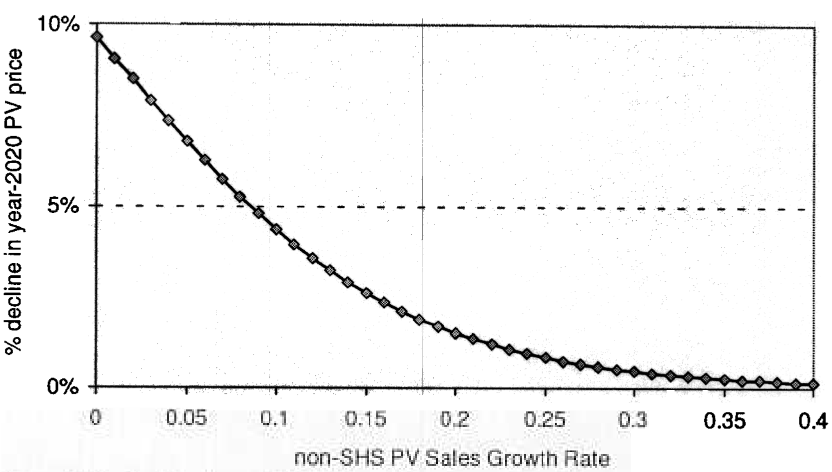

Figure 15.3. Decline in year-2020 PV module prices attributable to SHS markets assuming base case parameters but varying the non-SHS PV sales growth rate.

from projected overall PV module sales yields an estimated year-2020 PV price of $1.23, or only 1.5% higher than the projection that includes module sales for SHS markets.

In this base case forecast, SHS penetrate 11% of the maximum projected SHS market by 2020.[5] The assumed upper bound of 20,000 MWp of SHS 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.

The estimated impact of global SHS sales on PV module prices is sensitive to the assumed progress ratio. Figure 15.2 shows the percentage PV price decline attributable to SHS over the period from 2000 to 2020. If the progress ratio were to prove as low as 0.7, then the model predicts SHS 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 SHS sales on PV prices in this static analysis falls proportionately.

Figure 15.3 shows the negative relationship between the growth rate of non-SHS PV sales and the impact on module prices of the SHS component of the PV market.

[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 SHS costs. It is likely that these costs would come down if the number of SHS 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 (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).

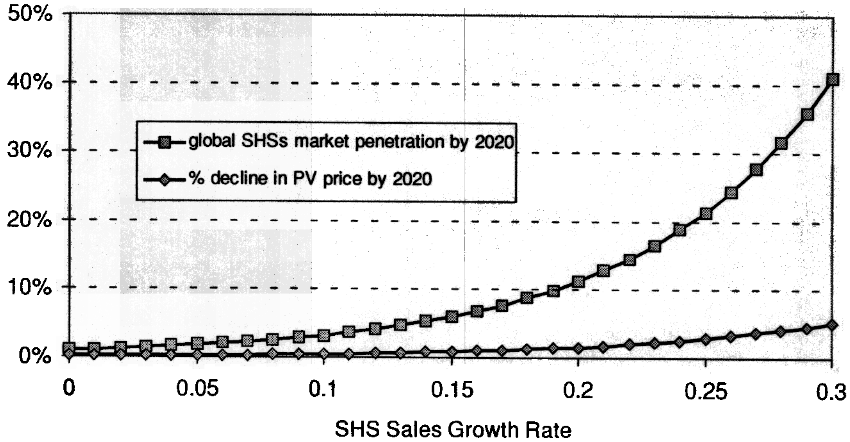

Figure 15.4. Decline in year-2020 PV module prices attributable to SHS markets assuming base case parameters but varying the SHS PV sales growth rate.

Figure 15.4 shows that it is also possible to vary the projected SHS sales growth rate. Holding the base case parameters constant, if annual SHS increase at 30% rather than 20%, by 2020 this yields 40% saturation of the SHS market and a price decline attributable to SHS of about 6%.

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

15.5 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 characterized as the percentage 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 15.5 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 commercialize clean energy technologies like PV.

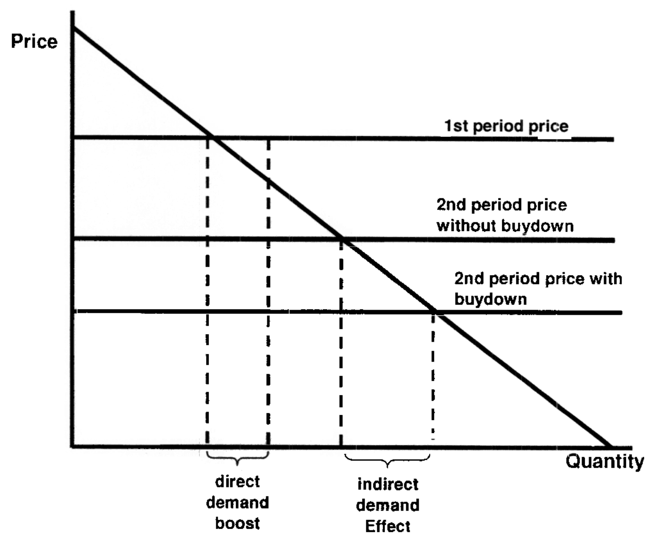

Figure 15.5. Two-period buydown.

15.6 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 SHS is unlikely to have an important impact on global emissions. Even if the entire potential market of 400 million households receives SHS, this would displace only approximately 20 million tonnes of carbon equivalent (tC) annually, or about 0.3% of global emissions.[6]

Thousands of rural consumers purchase SHS 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 (Energy Information Administration, 1998, and White House, 1998). 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 number and size of SHS installed since the technology is already cost-effective in this application.[7] Of course, the CDM can play a useful role only if the transaction costs involved in certifying emissions reductions for SHS are kept to an absolute minimum (Kaufman *et al.*, 1999).

In addition to direct carbon displacement, as noted every MWp of SHS sold helps to lower the global market price for PV. As PV prices fall, sales in existing markets increase 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.*, 2001). Similar distributed grid PV markets exist globally.

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

15.7 CARBON ABATEMENT IMPLICATIONS OF AFRICAN SHS MARKETS

As of 2002, there were approximately 840 million people in Africa, of which 690 million are in sub-Saharan Africa.[8] Precise estimates are unavailable, but assuming less than half of these people have access to grid electricity implies a potential SHS market of at least 60 million households.[9] A 50% penetration rate with average system size growing to 50 Wp (as prices fall and rural incomes increase) translates into about 1,500 MWp of total PV demand, or six times global PV sales of 250 MWp in the year 2000.

There are, however, a number of unique aspects to the African SHS 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 SHS dissemination. Rural South Africans generally view SHS as a second-best option relative to heavily subsidized 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 (Anderson and Duke, 2001).

15.8 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 (World Resources Institute, 1998). As of 2002, roughly 100 MWp of off-grid PV had been installed in Africa.[10] SHS account for approximately one quarter of this, with the remainder in telecommunications and various government and donor projects (e.g. water pumping, schools, and health clinics).[11] This is equivalent to just 0.03% of total grid electricity generated in the continent.

[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] 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.

[8] www.prb.org

[9] Assumes an unelectrified population of 420 million and an average rural household size of seven.

[10] Maycock (1996) suggests that Africa accounted for 10–13% of the global PV market in 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 subsidized grid-connected markets in industrialized countries have taken off). Assuming Africa maintained a 10% share implies that there has been about 100 MWp of cumulative off-grid sales in the continent through 2002.

[11] This assumes there will be about 150,000 SHS averaging 25 Wp each in Kenya and another 500,000 SHS 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).

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.[12] This is an aggressive projection since it is equivalent to providing a 50 Wp SHS for all 60 million currently unelectrified African households. Nonetheless, electrification efforts have often failed to keep pace with population growth in rural Africa, average system sizes should increase as SHS prices fall, and non-SHS markets may continue to drive overall off-grid sales. 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.

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[12] 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).

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