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THE VALUE OF PHOTOVOLTAIC ELECTRICITY FOR SOCIETY

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Abstract—This paper addresses several issues to be considered when assessing the value of PV electricity. The value of PV has been examined from various perspectives—consumer, utility, and environmental—and for central and decentralized PV systems. Aggregating these benefits leads to the value of PV for society. In this context, economic and ecological aspects have been considered. Furthermore, feedback from consumers drawing electricity directly from the sun have been taken into account. This is expressed mainly as energy conservation and load-shift effects triggered by changes in consumer behaviour due to decentralized PV systems. Finally, it is proposed that, collectively, the benefits of PV systems will ensure its continued promotion and development as an energy resource, resulting in a presumably slow but steady increase in market penetration.

1. INTRODUCTION

The high investment costs of photovoltaic (PV) systems are the major impediment to wider market penetration for this technology. Although its cost was reduced by some 70% between 1980 and 1990 in the United States (RMI, 1991), PV electricity remains approximately eight times as expensive as coal-fired electricity. However, the conventional economic comparison is distorted: (a) hidden environmental and health costs associated with fossil fuels are not generally included in energy prices; and (b) many conventional energy carriers are subsidized (e.g., coal in the FRG and nuclear power in France).

The supposition is that a higher market penetration of PV would be socially desirable;[†] therefore, an appraisal of the value of PV electricity for society is required. The value must be obtained by analyzing the benefits of PV from the perspective of consumers, utilities, and the environment.[‡]

The central postulate of this study is: If it were possible to bring together these benefits and integrate them into one comprehensive policy, the outcome would lead to a continuous development strategy over time rather than "prairie-fires" due to short-sighted promotion strategies (e.g., full-cost refunding). This would result, by and large, in correct market penetration.

The purpose of this article is to survey the scope of issues that must be considered when assessing the value of PV electricity. Due to the complexity of the problem, the framework has been sketched without going into either formal details or into quantitative investigations (e.g., deriving a model to calculate correct tariffs). Instead, all aspects that are of interest in this context have been summarized, providing a basic foundation and identifying parameters necessary to quantify dynamic feedback reactions for further investigations. In doing so, the economic and non-economic impacts of different types of central and decentralized systems have to be considered. Dynamic interactions and related benefits were also examined. The dynamic effects taken into account in this article are energy conservation through self-production of electricity, and conceivable market supply and demand curves.

The main considerations used to estimate the value of PV (from different viewpoints) are:

1. Consumers compare relative production costs and electricity prices. In this context, the effect of building integration on overall investment costs is of interest. Savings on investments are made because the PV element replaces a conventional building segment and no support structure for the PV system is needed.
2. Utilities compare the production costs with opportunity costs. For the utilities, the value of PV depends on the daily, seasonal, and annual load figures (e.g., the time of the daily peaks, the correlation to solar peaks, and whether the region is summer- or winter-peaking).
3. Governments must look for societal benefits or "avoided" social costs. For government, the most interesting question is to what extent is it justified to subsidize PV technology. The question of central "power stations" versus decentralized applications (e.g., building integrated systems) is of particular interest. More precisely, conceivable trade-offs between PV systems and energy conservation have to be taken into account. An indirect energy conservation effect is expected for decentralized systems because users of this technology become more cost

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[†] This paper does not discuss the energy payback time of solar cells. Recent studies report numbers of some 5 years. For further discussion, this justifies the presence of a social benefit.

[‡] The "environmental point-of-view" is considered the benefits to people resulting from less pollution and degradation of resources.

conscious and concerned with their electricity consumption than those without comparable systems. This will result in a reduction in demand.

This leads to the point that for society, the benefits of decentralized PV systems (either grid-connected or stand-alone) are higher than those of PV power stations. This follows from the following arguments:

1. No additional land area is needed,
2. The investment costs are reduced because of a less expensive support structure, and
3. There is an indirect energy conservation effect due to the involvement of consumers in their own electricity supply.

The literature on the topic is scarce. Krebs and Starr (1989) analyze the value and viability of PV-generated electricity for stand-alone versus grid-connected systems. A survey on technical and non-technical issues of PV-systems is provided by Bächler (1991). Lund and Peippo (1992) describe an approach for evaluating the cost-effectiveness of building integrated PV systems. A detailed analysis from the utilities' point-of-view is given by Weinberg *et al.* (1991). Awerbuch (1993) discusses the costs of PV in a utilities planning framework. Scheer (1994) provides an excellent survey on the socio-economic benefits.

The following section discusses aspects of consumer decision making and behaviour due to, and benefits of, PV systems. Section 3 summarizes the issues that must be explored from the utilities point-of-view. In the subsequent section, societal issues are examined. An outlook on what strategies are effective to reach the social optimum of market penetration completes the study.

2. PV ELECTRICITY FROM THE CONSUMER PERSPECTIVE

In this section we discuss issues of PV systems that are related to consumers. The most important questions are which conditions influence consumer willingness-to-pay (WTP) for a PV system.

A rigourous economic analysis that calculates the costs of electricity generated by a PV system leads to the conclusion that, except for some remote areas, there is no incentive for consumers to purchase a PV system for their electricity supply. Simultaneously, there is a growing market for PV systems (Flavin and Lenssen, 1992), even in the private sector[†] (RMI, 1991). It must be concluded, therefore, that there are also other parameters that have an influence on consumer decisions.

There is no uniform bulk of electricity consumer. Consumer decisions depend upon many socio-economic variables: education, colour, income, comfort, quality, size, design, energy efficiency, environmental concern, and last but not least, cost. Despite differences in income, personal concern (e.g., environmental awareness), and prohibitive investment costs for PV systems, some consumers still purchase these systems (see also Gregory, 1994). Furthermore, there is a specific group of consumers that use PV for purposes other than electricity production: architects. They find PV elements more and more attractive for new contemporary designs.

It is suspected that in many cases the problem is not purely related to monetary payback periods. The crucial point is whether PV systems are affordable as an initial investment. Some single-family households may find it more attractive to install a PV system instead of purchasing an expensive car. Architects will consider a PV panel as an element of building design if the additional costs justify the overall architectural improvement.

The following diagram examines different WTP scenarios for various consumers while discussing optimal subsidy strategies for governments. Figure 1 shows conceivable demand and supply curves for PV. The linear downward sloping curve represents the demand for PV systems. The demand curve is equivalent to the relevant WTP. The purchased quantity q (e.g., kW_p installed) increases with falling prices p (e.g., $\$/kW_p$). The supply curve is projected by the marginal production costs of a PV system. This curve is a concave slope due to economies of scale (e.g., mass production of solar cells). In the long run, perfect competition in the market will lead to the price p_∞. We see that there are two conceivable equilibria. The initial price of PV is p_0 and the supply curve intersects demand at the initial equilibrium with quantity q_0. For historical reasons we are "locked" at this point. There is, however, an equilibrium for the long-term price p_∞. We assume that there are substantial[‡] societal benefits of PV systems. A subsidy strategy launched by a government could then strive for reaching the point of the second equilibrium p_∞, q_∞.

Obviously, subsidies of $(p_0 - p_\infty)$ would shift the demand to q_∞. The idea is that the entire difference $(p_0 - p_\infty)$ does not have to be given to consumers: a percentage of this difference will suffice. In a discriminating market strategy this is the difference between the supply and the demand curve (e.g., σ_1 shows the amount of subsidies necessary to shift the demand from q_0 to q_1. At the maximum level, the amount of subsidies runs up to σ_{max}. Reaching quantities of $q > q_m$, the required amount of subsidies necessary to increase the market penetration declines again. The new equilibrium is reached at p_∞, q_∞; no further subsidies are provided. From this point on, market forces must takeover.

As a result, an efficient subsidy strategy will try to reach the point of lowest marginal production costs, the depicted conceivable long-term equilibrium in Fig. 1, with minimal distributed subsidies. This would lead to the long-term demand q_∞ for PV systems.

An important argument for the distribution of subsidies is consumers will change their electricity consumption behaviour due to the installation of PV systems, reducing their overall electricity consumption

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[†] We assume private consumers to represent all types of consumers other than public utilities.

[‡] This aspect is discussed in detail in section 4.

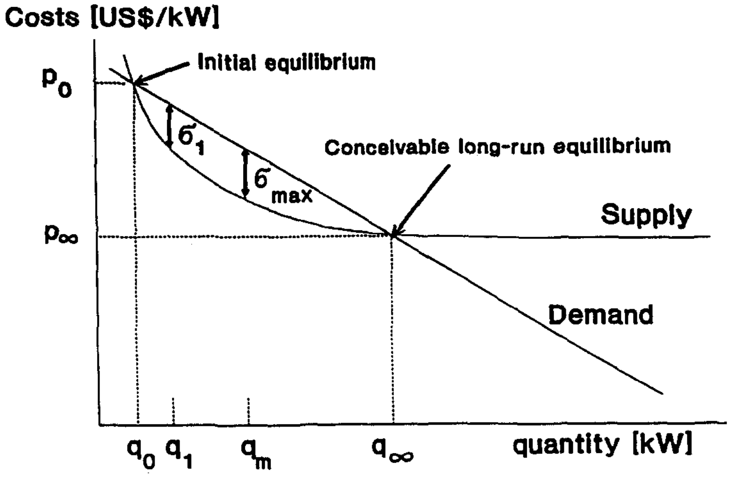

Fig. 1. Demand and supply curves for PV and initial versus conceivable long-run equilibria.

for the following reasons. Having their own electricity production plant (PV system) will influence their concern for energy use, serving as an educational device. They will maximize the amount of electricity they feed into the grid, thereby reducing their consumption. Furthermore, the so-called "meter-effect" will also contribute to a change in awareness and energy use. This effect takes into account that PV consumers read the electric meter more frequently (than the average consumer) and worry more about their consumption. These aspects will lead to a conservation effect as well as (moderate) shifts in the load profile due to a short-term change in consumer behaviour and long-term investments in energy saving appliances (e.g., compact fluorescent lamps). This decentralized conservation effect could lead to a considerable societal benefit.

3. THE VALUE OF PV FROM A UTILITY'S POINT-OF-VIEW

A utility generating and selling electricity considers the value of PV with respect to what it can contribute to the utility's[¶] objectives. For example, if PV contributes to peak shaving and thus become substitutes for expensive gas turbines or hydro storages, it should become an economically feasible technological approach. Another example is the power supply of remote areas where stand-alone PV-systems are an alternative to new and expensive distribution lines or diesel generators. The value of PV is calculated relative to the opportunity costs.

A utility will assess the value of PV by means of comparing the usual demand (load) profile with the electricity produced by the solar cells. This comparison is made for both daily and yearly load profiles. One important item is how well the solar option correlates with the utility's load shape on both daily and yearly levels. Figure 2 and Fig. 3 show these curves for Vienna, Austria.

[¶] *Objectives* is prefered rather than *profit* since, worldwide, most utilities are restricted from making excessive profits. (Consider the *rate-of-return regulation* in the USA or the *cost plus regulation* in Austria and Germany.)

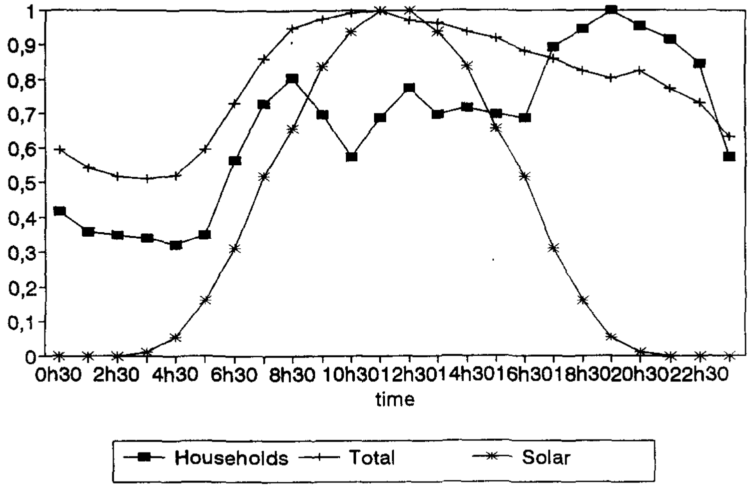

Fig. 2. Daily load shape of total electricity demand, a households electricity demand, and solar option, summer day (Vienna, Austria).

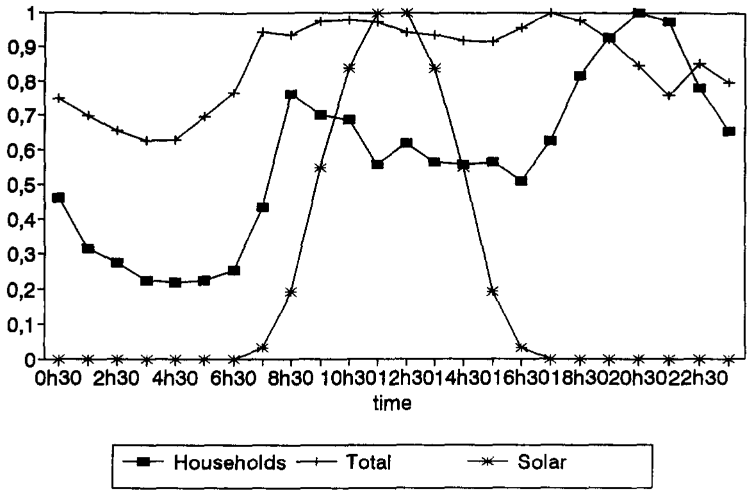

Fig. 3. Daily load shape of total electricity demand, households electricity demand and solar option, winter day (Vienna, Austria).

These comparisons are made because a utility analyzes two types of costs: the short-run marginal costs (SRMC) and the long-run marginal costs (LRMC). This analysis is based on daily and yearly cycles. Once the correlation is known for both levels, the utility will know how much electricity from the sun can be expected to meet on-peak demand. A comparison with a peak-load tariff and other options to generate on-peak electricity gives the cost limit for PV. The utility can decide whether it would be more efficient to construct conventional power plants or put its money into PV. This aspect is discussed very comprehensively in Weinberg *et al.* (1991).

A utility considering a PV option has several possibilities. It can construct its own PV power plants or it can purchase PV electricity. In the former case, the utility is required to pay high investment costs; in the latter, the utility must pay for every kWh fed into the grid. Furthermore, a utility can consider renting roofs for mounting PV systems. For example, in multi-family houses, this could be a viable alternative since tenants may have high transaction costs (e.g., negotiations with the landlord). It may be simpler for the utility because it can rent a whole roof and produce electricity almost directly at the place where it is needed. One of the most discussed issues in this context is, what price the utility should pay for a kWh. Should the price the utility pays for PV electricity even be higher than the electricity price the consumers pay the utility?

The kWh price a utility pays can be calculated from its overall objectives. The utility will, at each point of time t during the day and throughout the year, maximize the difference between revenues and expenses. The revenues are simply the amount of electricity $x_0(t)$ sold at t and the total generation costs $c(x_0(t))$:

$$\max_{x} p_{\mathrm{ele}} x_0(t) - c(x_0(t)) \tag{1}$$

If we consider an owner of a PV system who delivers all the electricity produced at t, $x_{\mathrm{pv}}(t)$, into the grid, we can calculate the price p_{pv} the utility will pay for a kWh at t:

$$\max_{x_{\mathrm{pv}}} p_{\mathrm{ele}} x_0(t) - c(x_0(t) - x_{\mathrm{pv}}(t)) - p_{\mathrm{pv}}(t) x_{\mathrm{pv}}(t) \tag{2}$$

The first derivation gives:

$$p_{\mathrm{pv}}(t) = c'(t) \tag{3}$$

The utility will then pay the amount of the marginal costs for each additional kWh produced. Now consider, that there is an additional conservation effect. More precisely, at the crucial point of time for on-peak demand, PV consumers may also reduce their electricity demand. Following Wirl (1989) the objective of the utility will be:

$$\max_{\Delta x} p_{\mathrm{ele}}[x_0(t) - \Delta x(t)] - c(x_0(t) - \Delta x(t)) - \alpha(t)\Delta x(t) \tag{4}$$

In this equation, we consider that the utility may pay a bounty α for every kWh saved. Solving this problem we obtain:

$$\left.\begin{array}{l} \alpha(t) = c'(t) - p_{\mathrm{ele}} \\ \alpha(t) = 0 \end{array}\right] \text{ if } c'(t) \begin{array}{c} > \\ < \end{array} p_{\mathrm{ele}} \tag{5}$$

This leads to the conclusion that if the marginal costs of production exceed the price for electricity at this point in time, the utility would pay a bounty α for every kWh saved. Furthermore, it is suspected that if there is an additional conservation effect linked to the PV electricity fed into the grid, the price the utility should pay will even exceed the amount of $c'(t)$. Moreover, if the $c'(t) > p_{\mathrm{ele}}$ condition holds, a government must consider paying a bounty for energy conservation if a societal benefit is expected.

The way consumers respond to different prices for PV (see Haas, 1994) also needs to be mentioned. We have to take into account three cases:

1. $p_{pv} < p_{ele}$. In this instance, the consumers will match their demand to the solar option and (perhaps) shift their demand to the utility's on-peak time;
2. $p_{pv} = p_{ele}$, where there is no incentive for consumers to change their load profile; and
3. $p_{pv} > p_{ele}$. With respect to this condition, consumers will try to maximize the amount of electricity they sell to the utility and, therefore, shift their demand to the off-peak time of the utility.

In practice two realistic conditions remain. The first is a buy-to-sell ratio of 1:1. This is leastly justified because of PV electricity is produced at (daily) on-peak demand times. The prevailing argument is that this policy causes no transaction costs for the administration. Yet, this strategy has to be revised if PV households are no longer insignificant forces in the market.

The other condition is a price for PV electricity higher than the market price. This strategy will be selected if considerable benefits are expected due to a shift in consumer load profiles that is favorable for the utility.

4. SOCIETAL APPRAISAL OF PV ELECTRICITY

With respect to society's point-of-view, it is important to determine if subsidies are justified and how an optimal subsidy strategy is portrayed. Therefore, the value of one kWh of PV-produced electricity for society is to be determined. We can estimate this value by analyzing the different effects of PV:

- Direct reduction of environmental externalities caused by electricity production and consumption due to PV electricity. The existence of this effect is demonstrated by Hohmayer (1992).
- Indirect benefits because of decentralized PV systems provoke energy conservation effects.

We obtain the over-all utility to society by bringing together the benefits of different groups:

Societal benefit = Consumers' individual benefits

+ Electric utilities' benefit

+ Producers' and Retailers' benefits

+ Environmental benefits.

Obviously, subsidies are required mainly for *environmental benefits* provided by PV systems. The benefits for other groups will emerge without additional incentives from government.

The crucial point is what other features have to be considered for launching efficient subsidy policies. Three questions are important in this context:

1. Should PV power stations be promoted in the same way as decentralized applications in buildings?
2. Should systems that feed excess electricity into the grid be treated similarly to small power stations that deliver every kWh to the grid?
3. Should there be subsidized tariffs or subsidies on the investment?

The answers are straightforward. They draw on the argument that the energy-conserving effect and the change in consumer behaviour and awareness occur only if there is a direct relationship between the consumers and the PV system. Hence, there is a higher societal benefit from decentralized applications than from power stations. And there is a higher benefit from systems that feed only *excess electricity* into the grid than from systems where there is no link between supply and demand. However, decentralized-produced and used kWh also lead to a societal benefit. These kWh should be subsidized to the same extent. Thus, subsidies for the investment are preferable to subsidized tariffs.

How high should these subsidies be? We consider two approaches. The first assumes that a government provides a certain amount of funding, S_{max}. It intends to maximize the benefits that can be drawn from this amount: it will try to maximize the installed PV capacity. Therefore, the optimal amount of specific subsidies per kW_p has to be calculated. This can be derived from the following optimization problem, eqn (6–8).

$$\max_{\sigma} P_p \tag{6}$$

s.t.

$$\sigma = \sigma(\mathrm{WTP}) \tag{7}$$

$$\sigma^* P_p^* = S_{max} \tag{8}$$

where σ is the specific amount of subsidies per kW PV; S_{max} is the overall amount of subsidies; P_p is the installed PV capacity due to the overall subsidies; and WTP is the consumer willingness-to-pay derived from Fig. 1.

We can obtain the optimal amount of specific subsidies σ^* and the maximal capacity P_p^* by taking into account the consumer WTP and the boundary condition (8).

The second approach requires estimating the extent of justified subsidies per kW_p. Therefore, we have to transform the revealed beneficial effects into monetary terms.

Consider the following example. The investment costs from a PV system are 16 US\$/W_p; assume an energy conservation effect of 20%. This saves electricity generated from fossil fuels. Savings of 1.2 kWh electricity are produced. The societal benefit estimated by Hohmeyer (1992) is between 5 and 27 c/kWh (1993 prices).[†] The amount of electricity produced by the

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[†] The numbers reported by Hohmeyer are (+)6.16 – (+)33.07 Pf/kWh (1982). The reported values have been obtained with an accumulated inflation factor of 1.38 for the period 1982–1993 and an exchange rate of 1.7 DM/US\$. However, other authors working on environmental costs have calculated other values. An excellent survey on environmental costs and benefits is provided by Twidell and Brice (1992).

PV system is 900 kWh/kW_p. An average societal benefit of 16 c/kWh is obtained. Taking into account the factor 1.2 and a capital recovery factor of 0.08 (lifetime: 20 years, discount rate of 5%), the justified subsidies amount to 2.16 US\$/W_p. This represents approximately 13% of the over-all investment costs.

A comparison of these two approaches reveals the range of subsidies. If subsidies of 10–15% of the investment costs also are considered optimal due to the optimization problem in eqn (1) (that takes into account consumer WTP), significant progress in market penetration due to justified subsidies can be assumed.

Another issue of interest are *transaction costs* for consumers. These are costs related to non-monetary aspects (e.g., finding out the cheapest retailer or the most efficient system). The evidence of the Austrian 200 kW program reveals that there are differences of some 30% for systems of similar size and quality (Wilk, 1993). Furthermore, there is a lack of information on the reliability of systems and on warranty. Hence, a government agency could compile this information and provide it freely to consumers; an important part of an effective promotion strategy.

5. CONCLUSIONS AND OUTLOOK

In this paper we have given a survey on the issues to be considered when assessing the value of PV electricity for society. The value of PV electricity will be seen differently by the consumer, utility, and environmental points-of-view. We obtain the value for society by summarizing the benefits for these groups. This leads to the following tentative conclusions. If brought together, these benefits will improve the economics of PV systems substantially. As a result, the market penetration will increase. Although this may be a slow process, it should be continous.

The reported investigations reveal another important point: decentralized PV systems should be subsidized more than power stations. Due to the fact that decentralized PV systems provide several environmentally-beneficial side-effects, the goal of the government should be to establish as many small systems as possible instead of fewer, large power stations because users of PV electricity will change their behaviour to a certain extent. They will try to match their electricity needs largely to the solar option and will conserve electricity. Moreover, decentralized PV systems lead to an important educational effect because consumers are better informed about electricity production. They will longer believe it "just comes out of the socket."

To bring about the benefits of PV electricity for society, the most important issue is that a continous promotion strategy should be implemented. Such a strategy has to consist of both subsidies for investments and fair tariffs. Moreover, the economics could be improved by integration of PV systems into buildings since there are savings through (a) the replacement of conventional building elements and (b) the lack of investments for the support structure.

Due to the benefits for different groups, the following instruments should be applied:

- There are justified subsidies a government should pay for decentralized PV systems. We estimate these subsidies to be about 2000 US\$/kW_p.
- Tariffs for PV: A buy-to-sell ratio of 1:1 is justified because PV electricity is fed into the grid at (daily) on-peak times.
- Information on prices for PV systems, methods for cost-effective installation, and reliability should be compiled by governmental institutions and distributed to interested consumers.

This leads to an important conclusion: Most of the parameters used to appraise the effective benefits are, by and large, unknown. That is to say, to obtain reliable numbers for these parameters, more practical experience is urgently required. Empirical data is required to answer the following questions:

1. How do the overall costs for purchasing a PV system change due to higher demand? More precisely, what percentage of the costs will be reduced?
2. What are the energy savings and the changes in the load profile of consumers with PV systems? And to what extent do these changes depend on the system size?
3. Are there cost savings due to decentralized applications (e.g., for building integrated systems because of less support structure and a replacement of conventional building elements)?

Hence, pilot programs, like the roof-top programs in Germany and Austria play an important role for the serious appraisal of the future prospects of PV electricity.

Finally, I would like to state my personal opinion. The transition to an environmentally-benign economy will reshape many features of today's society. Regarding the energy supply, there will be changes where solar energy use and energy conservation will proceed lockstep to provide energy services without harming the environment. The great success of solar energy will be that it demonstrates both a sustainable energy conservation effect due to a change in consumer awareness and a substitution of fossile energy carriers.

With respect to electricity supply, decentralized PV applications will play an important role. This is supported by the fact that despite the prevailing unfavorable economic conditions, the worldwide "market for photovoltaics is bursting at the seams" (Flavin and Lenssen, 1993).

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