

# ENVIRONMENTAL IMPACT OF PHOTOVOLTAIC ELECTRIFICATION IN RURAL AREAS

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## **ABSTRACT:**

The environmental impact of photovoltaics (PV) is discussed to ascertain how well it can aid solving the dual problem of meeting the demand for electricity in rural areas and of mitigating the energy-related environmental problems. It is noted that all emissions from PV are indirect and result mainly from the energy used in producing PV equipment. They are compared with the emissions that can be offset by the use of PV. It is concluded that PV is environmentally benign, and in some cases the cheapest way of providing electricity in rural areas. Nevertheless, its currently high costs and small electric capacity mean that there are cheaper and more effective methods for solving environmental problems in the short run. It is observed, however, that the costs of emission abatement are much higher if only the emissions from existing energy uses that are replaced by PV are considered than if the emissions and costs of alternative power production methods that are offset are also included. In the longer run, PV is seen to have very high potential for growth, lower costs, and environmental benefits. Issues affecting the success of PV dissemination in rural areas of developing countries are discussed, and policy suggestions are given.

**Key words:** photovoltaics, rural energy, energy pay-back time, emissions abatement, leapfrogging

## **1. INTRODUCTION**

Energy production and use is responsible for many environmental problems. As the environmental impacts of climate change, acid emissions, particle emissions, hazardous waste, and unsustainable use of biomass grow, so do the concerns of how to deal with the global energy consumption, which is expected to increase significantly over the next decades.

Simultaneously as the demand for global energy increases, there is a need to develop means of providing energy to developing countries. While a great deal has

been achieved in extending electricity grids, there are currently some two billion people without adequate energy services. In many rural areas the pace of extension has slowed down or been confronted with the need to modernize existing grids. As a result, stand-alone systems are common for rural electrification.

One possible solution proposed to deal with the dual problem of providing energy to growing populations and minimizing environmental hazards would be the use of photovoltaic (PV) technology. However, there are conflicting views as to how effectively this technology will aid in solving environmental problems. For example, an often expressed opinion is that PV technology is environmentally benign, but too costly to be effective in solving environmental problems such as global warming. At the same time, there are numerous programs around the world, trying to introduce stand-alone PV systems to rural areas. In these projects, the environmental benefits of PV are often expected to be significant. Many are national projects, but there are also those funded by international organisations, such as the GEF Solar project in Zimbabwe in 1993-1997 (Bacon, 1998; Mulugetta et al., 2000). Dissemination programs provide anything from a few hundred to tens of thousands of PV systems.

PV is one of the options for electricity services in rural areas. There it is often used to provide power for single households, schools or other public buildings. There are also mini-grids, which have a larger number of solar panels providing electricity to several households. Other common uses for PV are portable solar lanterns, water pumping, battery charging, street lighting, telecommunications, and vaccine refrigerators. In many cases the main competitors of PV are diesel generators<sup>1</sup>. Without electricity services, the rural energy use often consists of biomass, some kerosene and candles, and dry-cell batteries.

In this article, the environmental impact of PV is assessed in detail. Special emphasis is given to CO<sub>2</sub> emissions with a brief discussion on other emissions. In addition, the possibilities and costs of using PV in emissions abatement are considered. Furthermore, waste and recycling is discussed, as well as land use, and the impact PV may have on energy conservation.

An overview of social and economic issues affecting the success of dissemination of PV in rural areas of developing countries is also presented. Finally, the environmental and socio-economic issues are combined to assess what kind of situations would PV be most suitable for, and policy measures for gradually making conditions more adaptable for PV are presented.

## **2. GREENHOUSE GASES**

Energy use is by far the largest source of anthropogenic emissions of carbon dioxide (CO<sub>2</sub>), which is the main gas of the so-called greenhouse gases (GHGs). One way of reducing CO<sub>2</sub> emissions from energy production would be to use photovoltaic systems, which do not emit GHGs or other pollutants during their working time.

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<sup>1</sup> There are of course other options, for example wind power generators, and biomass gasification. In reality, however, diesel generator is the most common option. Modern wind power generators and biomass gasification technologies have a large potential also for rural electrification, and they can be cheaper than PV in some cases. However, they also face many problems similar to PV, such as introducing completely new technology to rural areas (see e.g., Hammad, 1995; Drennen et al., 1996). Renewable electricity production methods other than PV are not discussed in this paper.

However, there is a need to consider the energy-related emissions associated with the production of solar panels and other system components, as well as with other stages of the life-cycle of PV systems. For example, the modules have to be transported, installed, and after use, disposed of. The energy needed to perform these activities comes from sources that emit GHGs. Therefore, in order to estimate the relevance of photovoltaics in GHG abatement, it is necessary to consider both the emissions that result from the production of PV systems and the emissions that can be avoided by using PV. The common approach to this is to calculate first the energy requirements of manufacturing PV equipment and then the electricity produced by the PV systems. A measure of the relation between these two factors is the energy pay-back time (EPBT). The GHG emissions from the production can be calculated, and finally the emissions which would result from such energy use which is offset by PV can be estimated. As the final step, the costs of this GHG abatement can be calculated and compared with other approaches.

### **2.1 Energy Investment and Energy Pay-Back Time**

There is a significant energy input needed for manufacturing PV equipment. This manufacturing energy input has been reduced during the research and development (R&D) efforts of the past decades, although there is still room for considerable improvements. There are many areas which affect the energy input of PV, for example the choice of material for solar modules. The materials are usually divided into two categories, namely crystalline silicon and thin-films. The former consists of single crystal silicon and multi-crystalline silicon, the latter includes amorphous silicon and several different materials, such as cadmium-tellurium (CdTe) and copper-indium-selenium (CIS). Crystalline silicon panels have a better conversion efficiency, and they are more stable, but also more expensive. Up until now they have dominated the PV markets.

For crystalline silicon modules, the energy use is highest in the purification of silicon and manufacture of silicon wafers. Whereas in thin-film solutions, such as amorphous silicon (a-Si), the encapsulating materials and processing are more energy significant (Alsema, 2000). Recycling functioning silicon cells could have a significant impact on the energy consumption of the module production. Of course, recycling also consumes energy, which would have to be estimated in a more thorough life-cycle analysis.

Another important issue are the balance-of-system (BOS) elements, which often include support structures for the actual PV modules, wiring, charge controllers, and batteries. These components vary between PV systems, depending on the individual circumstances. Also for BOS are considerable future advances in EPBT possible (Frankl et al., 1998; Alsema and Nieuwlaar, 2000)

In rural electrification, the PV systems are mainly based on crystalline silicon and placed on rooftops. This reduces the importance of BOS in the EPBT for two reasons. First of all, generally rooftop systems require less material for supports than ground-mounted systems, and it is the production of module and array supports where the energy requirements of BOS are highest (Frankl et al, 1998; Alsema and Nieuwlaar, 2000). Secondly, in systems using crystalline silicon, the share of the BOS in EPBT is only some 10-30% of the total, depending on the type of installation, because the production of silicon crystal cells is very energy-intensive. Nevertheless, the

importance of BOS will increase if the energy requirements for module production can be reduced. Also, in stand-alone applications some energy storage has to be used. The production of commonly used lead-acid batteries is energy-intensive, and as batteries have to be replaced several times during the lifetime of the system, their impact on EPBT is considerable (Alsema, 1998).

In energy investment and EPBT calculations by Alsema (2000) and Alsema and Nieuwlaar (2000) the following methods were used: All energy use was calculated back to the extraction of primary energy carriers. A particularly important factor was the efficiency of electricity production. The conversion efficiency used was 0.35, and this factor was also used to calculate the primary energy equivalent of the electricity produced by the PV power system. The energy consumed in installation and dismantlement of the PV system as well as in transportation were left out of the calculations, largely because energy needed for some of these uses is negligible. For example, energy for transportation is likely to be only a few percent of the overall requirement (see Keoleian and Lewis, 1997). Also, especially in the case of decommissioning and recycling old systems, there was insufficient data for calculations.

The estimates from Alsema (2000) are presented in the Table 1. Note that the range of uncertainty is high, some 40%. The estimated improvements for crystalline silicon by the year 2010 will be the result of the introduction of "solar-grade" silicon and improved technology.<sup>2</sup> However, after these improvements, further energy efficiency improvements are estimated to remain only in the range of 1% per year. The energy requirement per watt will be reduced also as the module efficiencies rise (Alsema, 2000).<sup>3</sup> Aluminum frames would add another 400 megajoules per square meter ( $\text{MJ/m}^2$ ), which represents some 10-25% of the total energy investment (Alsema and Nieuwlaar, 2000).

Of the estimated  $1200 \text{ MJ/m}^2$  required for the production of frameless amorphous silicon modules, the cell material represents only 4%. Alsema expects the energy requirement for thin films to decrease by some 30% in the next 10 years, and a further 1% yearly after that.

EPBT is defined as the time it takes the (PV) system to produce enough electricity to compensate for the energy invested in the system. However, it is not only a measure of energy yield versus energy investment. Since the emissions from PV are always indirect, mainly from the energy used in production of modules and BOS components, EPBT of different modules and systems can be used as a proxy to indicate the indirect emissions from them.

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<sup>2</sup> Up until now the silicon cells in the photovoltaic industry have mostly been made from material that has been rejected by the micro-electronics industry for impurities. This silicon is of unnecessarily high quality for PV and it is believed that to use lower-grade silicon would substantially reduce the energy input. On the other hand, it could be argued that as long as the PV industry uses "waste" of another industry, the energy input to silicon production should not be included in the EPBT calculations for PV. This approach would reduce the energy input requirements and EPBT by more than two thirds (see Kato et al., 1998). According to Alsema and Nieuwlaar (2000), manufacturing solar-grade silicon has not been commercially feasible because of the currently small demand for it, but Dones and Frischknecht (1998) report that at least one company (Ethyl Corp., Albemarle) produces solar-grade silicon, consuming less than one-tenth of the electricity required for the purification of electronic-grade silicon.

<sup>3</sup> The output power of a PV module is expressed as peak watts (W<sub>p</sub>), or watts under "peak" conditions (temperature 25°C, irradiance 1000 watts per square meter ( $\text{W/m}^2$ )).

**Table 1: Module efficiencies and energy consumption in (frameless) panel production**

	Present	2010	2020
<b>Single crystal silicon (Sc-Si)</b>			
Module efficiency (%)	14	16	18
Energy consumption MJ/m <sup>2</sup>	5700	3200	
Energy consumption MJ/W <sub>p</sub>	41	20	
<b>Multi-crystalline silicon (Mc-Si)</b>			
Module efficiency (%)	13	15	17
Energy consumption MJ/m <sup>2</sup>	4200	2600	
Energy consumption MJ/W <sub>p</sub>	32	17	13
<b>Thin-film</b>			
Module efficiency (%)	7	10	15
Energy consumption MJ/m <sup>2</sup>	1200	900	
Energy consumption MJ/W <sub>p</sub>	17	9	5-6

Source: Alsema, 2000

The indirect emissions depend naturally on the source of energy used. Theoretically, it would be possible to have a PV production plant operating on solar energy. In such a situation there would be no emissions from the production energy. Currently, electricity used in manufacture plants comes from conventional power plants, with the corresponding emissions.

Unfortunately, the EPBT for PV systems is not easy to determine. It depends on a variety of factors (see Kato et al., 1998). As a result, values given for EPBT in the literature vary considerably, for example, Golob and Brus (1993) cite 15 months, and Kato et al. (1998) 12 years.

EPBT is very site-specific, as it does not only depend on the PV system itself but also on where the panel is used, with the regional differences in solar irradiation. As an example, Table 2 contains the estimates by Alsema and Nieuwlaar (2000) about the EPBTs for multi-crystalline silicon systems in different climates. The estimates are for grid-connected systems, instead of stand-alone systems which are the norm in rural electrification. The panels themselves are identical and much of the BOS equipment is similar, but the use of batteries in stand-alone systems could bring the EPBT of solar home systems (SHSs) to some 6-11 years (Alsema, 1998).

**Table 2: EPBT (as years) for multi-crystalline silicon PV systems for different levels of solar irradiation (as kilowatt-hours per square meter per year).**

Irradiation/ kWh/m <sup>2</sup> /yr	EPBT		
	2000	2010	2020
2200	2.5-3		
1700	3-4	1.5-2.5	<2
1100	Up to 6		

Source: Alsema and Nieuwlaar, 2000

The working time of a PV panel is often estimated to be 25-30 years, depending on maintenance and conditions in which it is used (Alsema and Nieuwlaar, 2000). It can be seen that especially in favorable climates, the EPBT is already short enough for considerable net energy yields. Future improvements could certainly improve the situation even further.

## 2.2 Emissions

Now that the energy requirements of the production of PV systems have been discussed, it is possible to estimate the GHG emissions from the production. Unfortunately, only the production phase can be considered here, as there is little information available of the other parts of the life-cycle, such as transportation and dismantlement, but the error is not likely to be significant, except perhaps for decommissioning and recycling (see section 2.1). BOS components have been included in calculations, although with some restrictions.

When manufacturing PV systems, the required energy for production is largely electricity. It contributes some 80-90% of the overall GHG emissions, with CO<sub>2</sub> contributing approximately 90% (Watson et al., 1996; Dones and Frischknecht, 1998). Some CO<sub>2</sub> is also emitted during material conversion processes, e.g. silica reduction (Alsema, 2000). Other GHG emissions include carbon tetrafluoride (CF<sub>4</sub>) which is used in aluminum manufacturing and in trimming solar cell edges. It represents less than 10% of the overall GHG emissions (as CO<sub>2</sub>-equivalents, using the IPCC global warming potentials). Nevertheless, the PV industry is looking for alternatives and for better methods for capturing and recycling CF<sub>4</sub> (Dones and Frischknecht, 1998; Fthenakis and Moskowitz, 2000).

The CO<sub>2</sub> emissions resulting from energy used in PV manufacturing process depend on the energy forms used in the production. In the following calculations the prevalent mix of energy sources in a region is used for both current production and estimates for the future, as the move to less carbon-intensive electricity production is likely to be slow (see Dones and Frischknecht, 1998). Different values for PV-related GHG emissions have been quoted in the literature. For example, Kato et al. (1998) calculated the CO<sub>2</sub> emissions for a 3 kWp residential grid-connected rooftop system using single crystal silicon modules, with a solar irradiation of 1427 kWh/m<sup>2</sup>/yr, and an estimated system lifetime of 20 years. All BOS elements were included. Their results range from 25 to 83 grams of carbon per kWh (gC/kWh), depending on how the emissions from silicon production were included. Importantly, they saw great possibilities for reducing these figures in the future. As a comparison, the average CO<sub>2</sub> emissions for electricity production in Japanese utilities are 126 gC/kWh (Kato et al., 1998).

Alsema and Nieuwlaar (2000) also considered grid-connected rooftop systems, using multi-crystalline silicon or thin films, a solar irradiation of 1700 kWh/m<sup>2</sup>/yr and panel lifetime of 30 years. They estimated that simplifying or leaving out certain elements from the calculations would cause about 20% error to the results (for example, only the aluminum supports of roof-integrated systems were included from the BOS components). They found that the CO<sub>2</sub> emissions for present PV technology are 50-60 gCO<sub>2</sub>/kWh (about 14-16 gC/kWh). The emissions from PV are then only

approximately 5-6% of those from coal (~ 1000 gCO<sub>2</sub>/kWh), and in a more favorable climate even less. While the CO<sub>2</sub> emissions from PV were approximately one-tenth of the present-day continental Western Europe fuel mix, of which about half is comprised of fossil fuels, they were higher than from nuclear power, wind power, and biomass (see Table 3). Again, significant emissions reductions are expected in PV technology in the next 20 years (20-30 and 10-20 gCO<sub>2</sub>/kWh in 2010 and 2020, respectively) (Alsema and Nieuwlaar, 2000).

**Table 3: Carbon dioxide emissions from different energy sources, gCO<sub>2</sub>/kWh. Continental Western Europe fuel mix**

Continental Western Europe fuel mix	570
PV	50-60
Nuclear	10
Wind	8
Biomass	20

*Source: Alsema and Nieuwlaar, 2000. Data for wind and biomass from IEA, 1998; for nuclear from Suter and Frischknecht, 1996.*

In regard to developing countries, diesel power is a very important alternative to PV. A comparison of GHG emissions from irrigation pumps in developing countries (solar irradiation 2000 kWh/m<sup>2</sup>/yr) showed that diesel pumps had some 1100 gCO<sub>2</sub>-equiv./kWh, whereas the emissions from different PV pumps were some 25-130 gCO<sub>2</sub>-equiv./kWh, or approximately one-tenth of emissions from diesel (Fritsche and Lenz, 2000).

### 2.3 CO<sub>2</sub> Abatement

Above, in Table 3, the emissions from PV were compared with other forms of power production. This is reasonable in the light that in industrialized countries it is hoped that PV and other renewables will eventually replace existing power production forms, and thereby lower energy-related CO<sub>2</sub> emissions. Meanwhile, PV is expected to help to offset new power production based on fossil fuels. In rural electrification in developing countries, however, PV technology brings a new form of energy to the people. PV electricity replaces existing energy forms, such as kerosene and biomass, but not other power production methods.

PV's impact on energy-use patterns is not, however, the same as that of extending the electricity grid. With PV there is only a limited supply of power available, as the costs per watt are still high. A solar home system (SHS) commonly has PV modules of some 15-50 watts. Electricity can therefore be used mainly for lighting and perhaps for powering a radio, TV, or fan. People will still have to rely on other energy forms for other energy needs, such as cooking. As a consequence, electricity is often an additional fuel and additional expense, changing the previous energy-use patterns only slightly, replacing for example candles or kerosene lanterns.

<sup>4</sup> The indirect emissions of PV were not included in the study.

When PV's environmental impact is considered, the question of baseline is crucial. The impact can be seen to be very different, depending on what PV is compared with. For example, in many studies the CO<sub>2</sub> emissions from replaced kerosene lanterns are calculated, and PV's environmental benefits are seen to consist mainly from these offset emissions. In other calculations, PV is compared with other electricity use, such as local diesel generators or coal power supplied by grids. The underlying assumption is that PV is not only replacing existing forms of energy but also preventing the introduction of competing power production forms. In this study both approaches are used.

Currently PV electricity is still much more expensive than conventional bulk-power production. Therefore large-scale utilization of photovoltaics would require significant financial investments, as in the form of subsidies. An example of a subsidized PV project is a Global Environment Facility (GEF) solar project in Zimbabwe, in which more than 9000 households purchased a PV system with a reduced-rate loan in the 1990s. As a result of this, GEF estimated that each household will reduce the use of kerosene by nine gallons a year. This would prevent the release of some 300-400 tons of carbon (tC) to the atmosphere annually (Kammen, 1996). According to Begg et al. (2000) the project cut CO<sub>2</sub> emissions at the price of 122-188 US\$/tCO<sub>2</sub> (= 447-689 US\$/tC).<sup>4</sup>

Begg et al. (2000) calculated the cost of CO<sub>2</sub> reductions in solar home system projects also in Kenya, arriving at the figure of 390-770 US\$/tCO<sub>2</sub> (= 1430-2820 US\$/tC). Clearly, SHSs were not a very cost-effective method for CO<sub>2</sub> emission abatement, and the projects related to cooking, such as improved stoves and family biogas digesters, were found to be preferable both in terms of cost and amount of CO<sub>2</sub> reduced. This latter point was caused by the fact that only a small portion of energy use in villages is electricity, and cooking is one of the most energy-intensive activities. For example, the biogas project cut emissions for the price of 7-18 US\$/tCO<sub>2</sub> (= 26-66 US\$/tC).

The above-mentioned study is also an example of an approach where only the existing energy uses are considered. If CO<sub>2</sub> abatement measures are considered in the light that they also offset the building of alternative power production methods the situation becomes different. In the rural areas of developing countries, diesel generators are often the most important competitor of PV. It has been shown that the CO<sub>2</sub> emissions from PV are only approximately one-tenth of those of diesel. For small loads in remote areas, PV is often also the cheapest option, or as cheap as diesel (e.g., Acker and Kammen, 1996; Byrne et al., 1998). In these cases, the costs of CO<sub>2</sub> abatement with PV are zero or even negative, as the electricity can be obtained for the same or lower price, with lower CO<sub>2</sub> emissions.

It seems impossible to make comparisons which would be applicable in every country and every situation, since the site-specific issues must be considered. At the same time, PV does not appear to be a very cost-effective way to combat global warming, because of the currently high price. It can also be noted that there is simply not enough module production capacity for PV to have a significant contribution to the global CO<sub>2</sub> abatement for the next decade or so (Alsema and Nieuwlaar, 2000). The capacity can be built over time, but there needs to be a demand for it. The demand, in

its turn, naturally depends largely on price, and therefore the reduction of costs will be the most important factor determining how soon PV will become feasible for wider use. The reduction of prices is discussed in more detail in section 4.

In the short run, while the changes in costs and production capacity for PV are taking place, energy efficiency, for example, may be a much more important and cost-efficient target area for CO<sub>2</sub> abatement. However, it should be noted that such abatement measures as energy efficiency do not bring electricity to those people who now lack it. In addition, the transition from fossil fuels to renewables would be advisable for many reasons, such as energy security and pollution abatement. There are also indications that the sooner such a change is started, the cheaper it will be in the long run (Kim et al., 2000).

But perhaps the most convincing argument for using solar electricity in CO<sub>2</sub> abatement is the almost limitless potential of the energy source. After all, the earth receives approximately 180,000 terawatt-years (TWyr) annually from the sun (Swisher and Wilson, 1993). While only a fraction of this energy is available for PV electricity, the comparison with the world electricity consumption, some 13,000 terawatt-hours (TWh) or approximately 1.5 TWyr in 1995, is overwhelming (IEA, 1997). Of course this energy is not distributed equally over the globe, the areas near the equator receiving much more than higher latitudes, but even the less "sun-rich" areas could benefit significantly from solar electricity, especially once the prices of the modules are reduced. As many developing countries have very favorable solar conditions, they could reap the best economic and environmental benefits.

### **3. OTHER ENVIRONMENTAL CONSIDERATIONS**

Despite the recent concern with global warming and CO<sub>2</sub> reduction, the "old problems" such as acidification and deforestation have certainly not disappeared. In this section, other important environmental issues will be considered. First, the contribution of PV to pollution abatement will be discussed, then the question of waste created in manufacture and use of PV will be addressed. Third, there is a discussion on the availability of land for photovoltaic installations. Finally, a tentative but far-reaching issue is raised, namely the guiding impact to energy efficiency which PV may have. The assessment in this section is largely qualitative, as there is not yet quantitative data available for all these issues.

#### **3.1 Other Emissions and Pollution Abatement**

Developing countries have understandably been reluctant to assume large responsibility for CO<sub>2</sub> abatement, emphasizing their right for economic and social development as well as the fact that so far the GHG emissions have mainly been caused by industrialized countries. Nevertheless, as mentioned, CO<sub>2</sub> is by no means the only emission from the energy sector. The growing emissions of acidic gases and other pollutants can be extremely significant, especially locally and regionally, as their impact on environment, health, and economy are often felt near the source of pollution. These impacts will have a profound effect on developing countries, unless the emissions reductions are taken seriously (UNDP, 1997). In that respect, investing in environmentally-sound energy technology is not a matter of global responsibility but simple self-preservation.

As noted before, there are no emissions from the PV modules during their working time. Instead, the emissions mainly take place during the manufacturing of the panels, and are mostly from the production of process energy. Obviously, the environmentally best results can be obtained when the production processes in the PV factory are as energy efficient as possible, when the efficiency of the electricity conversion is high, when there are adequate scrubbers for e.g. sulfur dioxide (SO<sub>2</sub>) or when the energy comes from cleaner energy sources, such as solar and wind power. The non-energy related emissions, such as possible chlorofluorocarbon (CFC) emissions from factories (see section 3.2), seem very minor compared to the emissions from energy use.

Replacing or offsetting polluting energy forms in bulk power production with PV would reduce overall emissions. Even though there are emissions from the energy invested into a PV system, the energy yield of the system is normally much higher than the energy invested into it. However, the energy mix used in rural areas in developing countries is very different from that used in industrial production of solar panels, and consists mainly of biomass, kerosene, etc.

As PV replaces some of the use of other fuels, such as kerosene, it slightly diminishes the overall emissions in rural areas. However, as discussed before, PV involves only a small part of energy use, as many end-uses, e.g. transportation and cooking, are beyond its scope at this stage. An important rural emission issue is the smoke from open fires and stoves as well as lamps and candles. Millions of people suffer from respiratory diseases caused largely by particulate air pollution from burning biomass (UNDP, 1997). PV can improve the indoor air quality by replacing kerosene lamps and candles. However, cooking, especially indoors, is a larger source of this type of pollution. Therefore, the introduction of better stoves would be more effective in cutting down emissions in rural areas. Note that the technology does exist for solar energy to be used in the form of solar cookers.

When it comes to alternative ways for producing electricity in rural areas, PV should be compared especially with diesel. In a life-cycle analysis of emissions from irrigation pumps in developing countries it was discovered that the acid air emissions were 50 times larger for diesel pumps (approximately 13 gSO<sub>2</sub>-equiv./kWh) than for PV pumps (<0.25 gSO<sub>2</sub>-equiv./kWh). In addition, with photovoltaics the problems with waste oils can be avoided (Fritsche and Lenz, 2000).

Despite these clear advantages, especially in the short run and in the national level, PV is not a particularly effective method for reducing pollution, because of the relatively small number and electric capacity of diesel and PV generators. Tackling larger power plants and introducing better fuels and vehicles for traffic are likely to be more effective ways of pollution control. Yet, it can be argued that in the long run the greatest value of PV lies not in the small-scale emissions reductions, but in its ability to offset the building of less sustainable power production structures, which are based on non-renewable energy sources. This aspect is discussed further in section 4.

### **3.2 Waste**

The waste from the use of PV is seen to consist of three elements, the discarded PV modules, the BOS components, and the waste from the production of modules. Naturally, also mining and refining of silicon and other raw materials cause waste, but they have been left out of the discussion.

Even though solar electricity has been used for decades now, the number of discarded photovoltaic modules has been fairly small. From around the mid-1980s onwards the production capacity has grown fast, growing perhaps as much as 30% in 1999 from the previous year (the numbers are still preliminary). Still, the yearly production is still only some 200 MWp, and the total installed capacity probably under 1200 MWp (Flavin, 2000). As the estimated lifetime of the panels is usually some 25-30 years (Alsema and Nieuwlaar, 2000), there are not very many panels needing disposal yet.

As a result, even though there are studies and theories about recycling PV modules (see e.g. Fthenakis, 2000), there is not yet much experience from actual, commercial applications. The volumes may still be too small to economically justify recycling at the moment. As silicon is the second most common element in the earth's crust, there is no scarcity of the raw material. Also, since silicon is not toxic, there is minimal leaching of hazardous materials even if silicon panels are not recycled. The aluminum used in frames may pose an exception to this, but frames are fairly easy to remove, and recycling aluminum is a well-established industry. Currently the industry seems reluctant to leave frames out altogether, but that would also be a possibility (Alsema and Nieuwlaar, 2000).

It is nevertheless obvious that the practice of just discarding modules wastes valuable high-grade silicon. Recovering functioning silicon cells might reduce the cost of modules significantly as reported in Bohland et al. (1998). This could also have an impact on the energy pay-back time (EPBT), as discussed above. In addition, it would add to the acceptability of the technology, by conforming to the general goal of utilizing waste as much as possible.

PV cell materials other than silicon present a very different picture. There are potential hazards with leaching of toxic materials, such as cadmium. During normal operation there is no leaching, and even if the panel is broken or there is a fire, there is only limited risk to humans from toxic materials. These materials are likely, however, to become a problem with disposal of large numbers of modules (Baumann and Hill, 1992; Steinberger, 1998). The issue of recycling may also become important as the metals used in these modules are relatively scarce. Consequently, recycling methods are being developed, and the technology exists at least for cadmium-telluride (CdTe) modules (Bohland et al., 1998). Even though the market for thin-films is growing fast, in the near future the majority of panels will probably continue to be based on silicon, as they still dominate the market (e.g., Shah et al., 1999).

The other elements in solar home systems are also of interest for recycling. Especially the commonly used lead-acid batteries not only contain enough lead to make the recycling profitable, but also represent a serious environmental hazard, if not handled appropriately. There are also more batteries than solar modules, since the batteries have to be replaced several times during the lifetime of the panels. While the number of discarded lead-acid batteries from PV systems alone may be too small to make recycling feasible, battery use in automobiles increases their number in circulation, making the recycling easier and cheaper to organize.

Effectual recycling systems for batteries exist in developing countries, but often only in urban areas. The more sparsely populated an area or the more rugged a terrain,

the more difficult it is to organize recycling. Batteries are also heavy, and as they contain acid, they can be difficult and even hazardous to transport (Lysen, 1994; Huacuz et al., 1995).

The manufacture of PV modules naturally also produces waste. For example, there is stainless-steel wire and slurry composed of silicon carbide (SiC), and some liquid wastes as well (Fthenakis and Moskowitz, 2000). A number of toxic or hazardous chemicals is used in the production, as well as CFC compounds which can deplete the ozone layer. Since many of these materials are commonly used in the micro-electronic industry, their monitoring and controlling are well established (Baumann and Hill, 1992). More environmentally sound solutions are also actively searched for, and different ways to recycle used chemicals are being developed (Fthenakis and Moskowitz, 2000). These chemicals are more likely to cause occupational health and safety hazards than significant environmental problems.

In the end, the main issue regarding waste products of PV is recycling, especially that of batteries due to environmental and health risks. The recycling of panels would be very advisable, as well.

### **3.3 Land Use**

One issue that has caused concern over large-scale use of PV has been that module installations require land which would not be available to other activities, especially agriculture. In rural electrification projects this issue has not been discussed in detail, as the number of panels has been very small, and the panels have commonly been placed on top of poles or on rooftops.

Even if PV is used in larger scale, land is not likely to become a limiting factor. Modules can be incorporated into roofs and facades, they can be placed over parking lots, gas station canopies, noise barriers, etc. (e.g., Kälin, 1994; Nordmann et al., 1998). There have also been scenarios where PV panels would be placed on poles or other structures, and crops could be grown underneath them (Lufti and Veziroglu, 1991; Goetzberger et al., 1998). Even if the land would have to be reserved for photovoltaics only, PV is not nearly as land-intensive as large-scale hydropower or biomass-produced electricity (Anderson and Ahmed, 1995). Of course each location is unique and it is possible that PV is not suited for some sites because of lack of available land, but on the whole this issue is not likely to significantly hinder the dissemination of photovoltaics.

### **3.4 Energy Conservation Effect**

While emissions and waste are concrete and documented issues, there are also impacts, which are less tangible, and perhaps harder to prove. An example is the possibility that the limited supply of electricity which is available from PV systems guides people to use energy-efficient technologies and to conserve energy. There is some evidence that indicates that this effect is connected to the choice between individual SHSs and a grid that supplies PV-produced electricity.

For example, Haas (1995:29) suggests 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."

The use of SHSs, which cannot economically supply much power, has probably increased the use of energy-conserving apparatuses, such as compact fluorescent lamps (CFL). The 11 W, 16 W, and 20 W CFLs generate the same luminosity as 60 W, 75 W, and 100 W incandescent light bulbs, respectively. In the Cook Islands, for example, the government supplied CFLs to the consumers free of charge, and the demand for power in one of the islands dropped from 21 kW to 5.6 kW. The Ministry of Energy of the Cook Islands has even considered banning incandescent light bulbs altogether (Yu et al., 1996).

If the use of individual SHSs can promote energy efficiency, the introduction of PV to the rural areas may have more impact on the future energy sector than anticipated. This issue certainly merits further study in order to find out, for example, whether the effect really takes place everywhere where SHSs are used, and whether it will last even if they are later replaced with other power production methods, or if it is merely a temporary response to scarcity of electricity.

#### **4. LONG-TERM POSSIBILITIES**

In this section long-term possibilities of PV are discussed. Largely all the considerations presented here apply also to other renewable electricity production methods. The other renewables are not discussed in this paper, but they are likely to contribute much to the future energy solutions globally and within the developing countries.

Based on the issues presented above it can be noted that while PV is an environmentally benign technology, there are still certain matters which require further improvements, such as the recycling of modules and BOS components. At the same time, it should be noted that the currently high costs and limited electric production capacity mean that PV is not yet a very effective or cost-effective tool in combating certain individual environmental problems, such as climate change or acidification. At least in the short run, there are a lot of other measures which are more effective and less expensive. In addition, some energy-related environmental problems, such as deforestation caused by firewood harvesting, are at least currently largely outside the scope of PV which is not suited for cooking.

In the long run, however, it may be wise for several reasons to move towards solar electricity. First of all, as noted, it is an environmentally benign way of producing electricity. Secondly, solar irradiation is a practically inexhaustible energy source. Use of PV can also help national energy security as it diminishes dependence on imported energy. In addition, many experts believe that dispersed, modular energy systems are becoming more important. They help to avoid the losses of transmitting power across long distances, and reduce the expenses of enlarging power production and distribution systems to meet the growth of demand. Also, even now PV is the cheapest way of providing electricity for small loads in some areas, due to remoteness of the site of use, which results in high fuel transportation and operation and maintenance (O&M) costs (e.g., Acker and Kammen, 1996; Byrne et al., 1998).

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<sup>5</sup> The theory of "energy ladder" states that users move step by step from low-quality fuels such as biomass to more versatile and "modern" fuels like electricity.

Cabraal et al. (1996:19-23) discuss how the load, the distance from an electricity supply line, and the density of household connections affect the break-even point where the costs of extending the grid and using PV are equal. However, it is not always the costs that prevent people from taking a connection to the grid. Acker and Kammen (1996) report also bureaucratic and institutional barriers for getting a connection. Therefore, even though they calculated the break-even point in Kenya to be 8.8 km from the power supply line, they discovered that very many systems were to be found less than 5 km from the grid. Similarly, van der Plas and Hankins (1998) found in their survey of 410 solar electricity systems in Kenya that the average distance to grid at the time of purchase was only 3.7 km. Since the electric utilities in developing countries are often struggling with financial difficulties, they may lack the ability to invest in rural electrification at all.

Clearly other factors than costs affect the dissemination of PV systems. For example, PV can be more reliable than its competitors. PV can also be felt to be safer than diesel generators (Acker and Kammen, 1996). Its modularity is another important factor, as reported by van der Plas and Hankins (1998). Of course, photovoltaics also suffer from comparison with the alternatives, for example due to the daily and seasonal variations in availability of PV electricity.

In relation to rural electrification, there may be a special advantage in introducing PV to developing countries, namely "leapfrogging". The term leapfrogging refers to a situation where a country (or a region) moves directly to the best currently available technology, "jumping over" the stages through which other countries have passed. It is possible that this leapfrogging can take place also in household energy use, instead of a slow climbing of the "energy ladder".<sup>5</sup> Goldemberg (1998:730-731) describes the issue very graphically: "The PV-CFL solution [PV used with compact fluorescent lamps] leapfrogs over its alternative: a large, expensive electric generating station, sending power over miles of transmissions and distribution lines, supplying a bulb that ultimately converts less than 1% of the original fuel energy to light".

It can be said that in respect to leapfrogging the value of introducing PV to new areas is not as much in the small amounts of emissions reductions now, as in the creation of a local infrastructure, which in its turn can prevent the building of less sustainable structures. For example, an extensive grid, transmitting power derived from non-renewable energy sources, can be very expensive, waste electricity over the long transmission lines, and provides energy derived from an environmentally unsound source. Leapfrogging may be the only way through which the developing world can achieve significant economic growth without huge environmental cost.

Stand-alone PV systems alone cannot, however, provide enough energy to avoid these costs. First of all, current SHSs commonly provide only some 15 to 50 watts, and are therefore not suitable for thermal applications. The more complete transition to electricity use in households cannot really take place with PV until the quantity of supply is equal to grid service. This may happen over time, as the experience on PV

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<sup>6</sup> The manufacture of PV modules requires considerable know-how as well as capital. Therefore it is not possible to produce modules in most rural areas, or even in every country. The BOS components, however, can often be produced within the country of use. Domestic products are often cheaper than imported ones, and can for example lower the risk of fluctuating currency rates (Acker and Kammen, 1996).

increases, and the prices are reduced. (Of course, even now solar water heaters and solar cookers allow the use of solar energy for thermal applications.)

Eventually, especially in urban or semi-urban areas, there is likely to be a transition from stand-alone systems to grid-connected systems. In industrialized countries, the research, development and demonstration efforts are already largely directed towards grid-connected systems. However, it is technically infeasible to introduce very much intermittent energy to the grids (for example, the National Grid Company of the United Kingdom now allows 20% of peak capacity from intermittent sources (Milborrow, 2001)), and of course energy output of PV systems stops entirely at night. Therefore with increasing use of PV some sort of energy storage system becomes necessary. In addition, electricity represents only a portion of all energy use. There is a need, for example, for “ecofuels” in the transportation sector (Coiante and Barra, 1996). As a result, a new energy structure will probably emerge in time, perhaps based on hydrogen. In such a structure the hydrogen produced with (PV) electricity will serve both as an energy storage and a vehicle fuel.

But the first steps in reaching this kind of PV-hydrogen structure are the creation of PV infrastructures, including industry<sup>6</sup>, retail and maintenance services, legislation, and financing mechanisms, as well as the lowering of PV costs. From this point of view, the use of PV now serves two goals: Firstly, it enables the creation of necessary economic and social structures for further, large-scale use. Secondly, the price of the technology is likely to continue falling through increased knowledge, experience and production of PV systems, which all relies on continuous demand.

This phenomenon of lowering costs resulting from increased production can be studied through experience (or learning) curves. The costs of different technologies can often be seen to decline by a steady percentage (= learning rate) over each doubling of cumulative sales. In PV-module production between years 1968-1998, the cumulative installed capacity doubled more than 13 times, from 95 kW to 950 MW (Harmon, 2000). During this period, the module costs declined by an average of 20% each time the total cumulative installed capacity doubled (Harmon, 2000; Luther, 2000). Because the module costs represent only 40-60% of the total installation costs, also the price reductions in BOS components are very significant. These vary much more than the module costs, and there is less historical data available. The cost reductions for BOS have, however, been equal to or even greater than for PV modules (Harmon, 2000). However, the price of SHSs varies considerably across countries and projects (Cabral et al., 1996).

In the 1990s, the growth of PV-module production was rapid, more than 10% yearly since 1994, and 30% in 1999. The price of modules also declined sharply in 1999 to 3.50 US\$(1998)/Wp (Flavin, 2000). If we assume that the production grows yearly 10% and the learning rate holds steady, the module price should fall to about 2.25 US\$(1998)/Wp in a decade, enabling PV to gradually conquer new niches. The total cumulative installed capacity would be some 5250 MW. Once the volume of PV is large enough to have a significant impact on environmental problems, the price will have presumably been reduced to competitive levels. Great potential for price

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<sup>7</sup> In fact, so far most of the subsidies and R&D efforts, aimed at bringing the costs down, have indeed taken place in the industrialized countries (Watanabe, 1999; Flavin, 2000).

reductions exists especially in the field of thin-films (e.g., Shah et al., 1999). Zweibel (2000) expects that the production costs for thin-film modules could fall to 0.3-0.5 US\$/Wp in the future. This would probably drastically improve the position thin-film modules hold in the market.

Analysis of several global energy scenarios (Nakicenovic et al., 1998 and 2000; Riahi and Roehrl, 2000) indicates that by 2050 the investment costs for PV systems could approach the level of conventional power production. PV electricity production is highest in the scenarios where there are more stringent CO<sub>2</sub> limits, the median being 37 exajoules (EJ or 10,300 TWh) in 2050. In those scenarios also the costs of PV are lowest.

In cases where PV is otherwise equal to the alternatives, it certainly makes sense to use the environmentally benign choice. These situations exist in many developing countries. In most cases, however, the costs of PV are higher than those of the alternatives. It has been argued that increasing the production and use of PV, in order to lower the costs according to the concept of experience curves, should be the responsibility of industrialized countries. These countries have more financial resources, more PV experts and laboratories, and arguably more responsibility in stopping the climate change.<sup>7</sup> The PV industry is also largely in the hands of companies based in the industrialized countries.

There are clearly two conflicting priorities. One is to guide the energy structures of developing countries to “leapfrog”, in order to avoid extensive damage to the environment of these countries, the other is to ensure that the technology is used by people who can really afford it, and that people receive the kind of energy services they really need. One way of overcoming the conflict of these priorities is to choose right kinds of areas for PV dissemination efforts. The criteria, social, economic, and environmental, which can be used for such choice, is discussed in the following section.

## **5. CHOOSING SITES FOR PV DISSEMINATION**

Even though the emphasis of this paper is on the environmental impact of the PV, it has to be noted that the main reasons for rural electrification are usually the social, and sometimes the economic benefits of electricity. It is difficult, for example, to compare PV lighting and kerosene lanterns only in terms of environmental impact, as electricity provides so much better lighting conditions. Naturally, there are also many end uses that specifically require electricity, such as television. PV certainly has an important value in bringing electricity to rural areas, regardless of the environmental value.

Whatever the reasons for introducing PV to the rural areas of developing countries, certain practical issues have to be resolved. There have been many kinds of problems with the PV dissemination projects. Some of these have been the result of technical failures, but very often the problem lies in the infrastructure of the area where PV is being introduced. PV technology is new, and proper installation, maintenance and other after-sales services are not always easy to arrange. There is need for competent technical personnel and for inventive financing methods. If the infrastructure for these services is lacking, as it often is in rural areas, their establishment takes time and effort.

Perhaps the largest barrier is the high manufacturing cost of PV equipment, but there are also other economic issues. These include high taxes or import duties, which may increase the retail price considerably (Acker and Kammen, 1996). Therefore, domestic production of equipment is advisable, provided the quality can be maintained. This also creates jobs. In addition, since the cost of PV electricity consists mainly of the price of PV equipment which often has to be purchased all at once, there is a need for appropriate financing methods.

The social issues affecting the success of PV dissemination include training professional personnel for installation and after-sales services, and users for everyday maintenance. This is made more difficult by a low education level, lack of experience with electricity, and possible language barriers (Huacuz et al., 1995).

Problems with PV systems do not only mean difficulties to the users, but also for the dissemination process, for it is repeatedly noted that in developing countries people most often hear about PV through their relatives and neighbors (Acker and Kammen, 1996). Negative experiences are likely to be recited widely and to hinder the dissemination significantly. Clearly a crucial point in all PV projects is the quality of products and service. Often it is not the quality of PV modules, which causes the problems, but of the BOS or services (Liebenthal et al., 1994; Lorenzo, 1997). The problem is further aggravated if there is lack of consumer protection.

There may also be other regulatory and institutional barriers. For example, there can be laws that make it impossible to establish new energy service companies (ESCOs). ESCO is a very general term for an institution which can take many forms, from a small non-governmental organization to a national electric utility. The key feature is that the ESCO can sell energy services but retain the ownership of the hardware (Cabraal et al., 1996). These ESCOs have sometimes been seen as the most effective method for PV rural electrification, as they can operate close to the customers, and often are able to offer PV equipment on a rental basis. Renting can significantly reduce the risk of the customer, in case of technical or economic problems. In addition, it takes full advantage of the modularity and reversibility of the technology. For a more detailed discussion on these and many other practical questions, see Bacon, 1998; van der Plas and Hankins, 1998; Mulugetta et al., 2000.

It should be noted that the commercial dissemination of PV in developing countries is based on stand-alone systems, purchased or rented by households. Small centralized PV plants are used often in water pumping projects or development co-operation projects targeting whole villages. The following discussion concentrates on the possibilities of creating PV markets. In the sections 5.1 and 5.2 practical questions of PV dissemination are combined with the environmental considerations, and two "imaginary case-studies" are presented. The first one (Pro-PV) is an example of an area, where PV rural electrification would have the most beneficial environmental impact, and where PV dissemination projects would have the greatest chances of success. The second one is called Con-PV. This name should not be interpreted to mean that the area would be completely unsuitable for PV, rather, it is where PV dissemination is less likely to succeed, and where environmental problems are not helped as much by PV use. Therefore it can be advisable to direct the active dissemination efforts at first to Pro-PV type areas.

These “imaginary case-studies” are idealized cases, exact matches of which are not likely to be found anywhere. They should be seen more in the light of “checklists” of characteristics and conditions which justify from the environmental point of view the PV dissemination efforts and influence their sustainability. Areas similar to these are likely to be found in very different countries around the world, even so that there can be both Pro-PV and Con-PV type areas within a single country.

### **5.1 Pro-PV Area**

In the Pro-PV area electricity use is on the rise. Environmentally unfavorable forms of energy (such as coal power or diesel generators) are an important option for electrification. Possibly the environmental impacts of conventional electricity production (such as acid deposition) either are already problematic in the region, or are expected to become so. The area has a relatively large rate of sunshine per day throughout the year. In other words, the environmental problems associated with energy use could be helped with cleaner electricity production methods, such as PV.

At the same time, high population density allows for effective installation, maintenance, and repairs of PV systems. There is also enough wealth in villages, so that at least several percent of households can afford PV electricity. Another possibility is that the government or some other institution is willing and able to subsidize PV considerably. There are also people with suitable technical capabilities, who can be trained for PV installation and maintenance.

In addition, the Pro-PV area has such institutional capabilities as readiness to create companies to start sales of PV equipment, or organizations that can serve as an ESCO to provide electricity services (through rent, leasing, etc.), and/or offer loans for buying solar electricity systems.

The consumer protection practices are reasonably developed and there are enforceable quality standards on equipment that is sold. Also, taxes, duties, and legislation do not discriminate against PV and may even help the development of local retail companies and ESCOs.

### **5.2 Con-PV Area**

In the Con-PV area, the energy-related environmental problems are not likely to be solved with the use of PV, as they do not result from electricity production, but for example from unsustainable use of biomass. (Conventional) electrification has been slow and is not expected to speed up in the near future. Therefore the offsetting of new, unsustainable, electricity systems is not a priority.

This area is sparsely populated, making it difficult to maintain an effective network of PV retail and maintenance on commercial terms. PV technology is too expensive for an overwhelming majority of the people and subsidies are not available or are not considered appropriate. It is also difficult to get locally available competent technical staff.

People investing in PV are likely to suffer from inferior quality products, and lacking consumer protection, due to institutional weaknesses. Government policies also hinder the market development through high import duties or legislation that does not allow the formation of small-scale electricity service companies.

However, even in these Con-PV areas small steps can be taken to enable the local

people, energy planners, and companies to start creating the demand, before pushing the technology from the outside. This would help to bring closer the time when it is sensible to start more aggressive projects to disseminate the technology.

Examples of such steps are the improvement of consumer protection and creating and enforcing quality standards on equipment that is sold. This would not have to be started from scratch, as there are international standards for PV panels and also universal, though flexible standards for BOS components (Egido et al., 1998).

It is also possible to rethink taxes, duties, and legislation, and to ensure that they at least do not unduly favor other energy forms at the expense of PV, but instead perhaps even help the development of the national PV industry, retail, and ESCOs.

These methods do not represent as much promotion of the technology as removal of the obstacles. A significant advantage of this approach is that it does not demand as much contribution from the national budget as subsidies. It is also noteworthy that even in less favorable conditions there seem to be people who are both willing and able to pay for PV systems, even in cash. It seems that at least the cheapest way of creating markets is to allow these people to buy on their own, without subvention efforts. Eventually this will bring about changes in the infrastructure that will allow the market growth and price reductions.

In addition, it is possible to electrify schools and clinics for which donor money may be available. It is, however, important to make sure that they are not isolated projects, each with different technologies and companies, as in such cases the information and experience is not easily transmitted from one project to another. In addition, there is a risk that such projects hinder the natural growth of domestic PV companies, but at least initially they can contribute to the local capacity building through training and experience gained (Acker and Kammen, 1996; Mulugetta et al., 2000).

## **6. SUMMARY AND CONCLUSIONS**

As there are no emissions from PV systems during their working time, all emissions are indirect, and mainly result from the production of process energy. The emissions per unit of electricity are considerably lower than those resulting from the use of fossil fuels. They are, however, high enough to warrant continuous R&D efforts to lower the energy investment required to produce PV modules and other components.

Another important issue is waste. While the most commonly used silicon-based modules are not likely to cause an environmental hazard even if abandoned, their recycling could result in considerable improvements in energy pay-back time and therefore in indirect emissions. It could also lower the price of modules significantly. Recycling of panels has not yet been established on a commercial basis.

A more acute issue is the disposal of used lead-acid batteries from stand-alone systems. Recycling of batteries is an established industry also in many developing countries, but especially in the rural areas it may be difficult to arrange on a market basis. Therefore, special attention should be paid to this issue, especially in organized projects.

Overall, it can be said that the negative environmental impact from manufacture and use of PV is slight, though there is certainly room for improvement. This does not

mean, however, that the use of PV in rural electrification could markedly improve the environmental situation in the short run. This is due mainly to continued high costs and small capacity of PV industry. Certain energy-related environmental problems, such as deforestation resulting from over-intensive firewood gathering, are not likely to be helped significantly with the use of PV.

It was shown that currently there are other emission-abatement measures in rural areas which are likely to be both more effective and less expensive, such as solar cookers. However, these methods often do not include electricity production, and the benefits of PV and its cost-effectiveness in solving environmental problems increase markedly if PV is not compared only with the existing energy uses, but also with the alternative electricity production methods. The main competitor, diesel generators, are often no or little cheaper than PV for small loads, and their negative environmental impact is significant compared to PV. Clearly special emphasis should be given to the choice of the baseline in these calculations.

On the whole, while undue optimism should be avoided, there is no reason to be very pessimistic, either. There are indications that the price of photovoltaics will likely continue to fall rather rapidly. More stringent carbon dioxide abatement policies over the next decades would be likely to increase the pace of PV dissemination, especially in industrialized countries. This growth of PV industry would in turn lower the costs more quickly, helping dissemination to developing countries. The source of energy, sunlight, allows virtually limitless expansion. Many developing countries are situated so close to the equator that they have a great potential for utilizing solar irradiance.

The social reasons are the most important objectives in rural electrification. Even if positive environmental impacts may not justify the expense of using PV, the other benefits support it. The most important thing is to be aware of all the benefits and costs of both solar electricity and its alternatives, and to be able to choose accordingly.

Affecting these choices are also the difficulties that can be encountered in introducing PV to rural areas. There are many practical issues which have to be considered. There has been concern that PV is being pushed to areas, where the necessary infrastructure is lacking. To provide better understanding of qualities which make the regions suitable for PV, two "imaginary case-studies" were presented.

It could be seen that PV is best suited to areas with more developed economic, technical and institutional infrastructures, and with electricity-related environmental problems. It may be best to concentrate the active dissemination efforts to these areas. Elsewhere it is possible to develop the infrastructure, legislation, etc. and allow the markets to provide PV systems to those who already can afford them. Eventually the market and infrastructure development will allow also poorer people to purchase the electricity generating equipment or energy services.

However, especially in regard to the Con-PV area, it should be noted that this technology has the ability to bring reliable electricity to areas where it would otherwise be impossible, or at least very costly, to use any other form of electricity generation. For this reason especially schools, clinics etc., which serve an important function in the communities, could be fitted with PV even where it requires continuous outside investments in money and time, and no significant environmental benefit can be obtained.

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