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AGRICULTURAL ECONOMICS
STAFF PAPER

PHOTOVOLTAIC TECHNOLOGY:

MARKETS, ECONOMICS, AND DEVELOPMENT

by

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September 1993 **SP 93-18**

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PHOTOVOLTAIC TECHNOLOGY: MARKETS, ECONOMICS, AND DEVELOPMENT

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Photovoltaic (PV) electricity has been widely supported as a remote energy source for developing countries. In response, the production and shipment of PV modules has steadily increased throughout the past decade, often marketed through the auspices of technology transfer and financed by international development aid. This paper investigates the motives, economics, and development implications of PVs in rural electrification. The implications of subsidizing a PV market rather than investing in further PV research and development are explored.

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I. BACKGROUND

Photovoltaic (PV) technology was first used in the U.S. for spacecraft applications in the late '50s. The active space program of the 1960s was responsible for establishing silicon solar cell arrays as the most economical and reliable source of power in space. PVs gained attention for terrestrial power during the oil shocks of the 1970s. Between 1975 and 1985, U.S. federally directed and funded PV research and development was largely responsible for reducing factory prices from over $600/W_p$ to $5/W_p$,[1] increasing module efficiencies from 5% to 15%,[2] and raising solar cell lifetimes to 20 years or more (SERI, 1988).

With the change of the U.S. Federal Administration in the 1980s came a deemphasis on renewable energy research. Federal PV research funding fell from $150 million in 1981 to a sustained $35 million during the late '80s (Firor et al., 1993). Since the formal conclusion of the Flat-Plate Solar Array Project[3] in 1986, world PV production has more than doubled from 26 MW (megawatts) to 58.6 MW in 1992, however average factory module prices have yet to break the $5/W_p$ barrier (Maycock).

Milli-watt applications in consumer products such as calculators were the growth market of the 1980s and still account for the largest share of U.S. applications (see Table 1). On a larger wattage scale, U.S. utilities have invested in more than 100 PV projects, but all in a research or demonstration capacity (Firror et al., 1993).

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[1] In 1985 dollars; W_p relects the manufacturers rated peak wattage output.

[2] The efficiency of the PV cell in converting energy from the sun into DC electricity.

[3] An 11-year $235 million research and development effort managed by NASA's Jet Propulsion Laboratory. The Project, a major component of the National Photovoltaics Program, incorporated a government-industry-university research effort on flat-plate PV arrays and crystalline silicon technology (SERI, 1988).

TABLE 1
U.S. PV Sales: 1989

Application	Percent of Total
Consumer Goods	22%
Communications Systems	20%
Buoys and Other Transportation-Related Systems	9%
Water Pumping	6%
Grid Interactive Electric Generation	10%
Remote Electric Generation	20%
Shipped to Original Equipment Manufacturer (a)	12%
Other	1%

(a) Use not recorded in survey
Source: U.S. Department of Energy, Energy Information Administration, Annual Energy Review 1990, DOE/EIA-0384(90).

Table 1 describes U.S. PV consumption. For U.S. PV production, however, the largest market is in exports. Over 50% of U.S. production was exported in 1991. In Japan, recently the largest producer of PVs in the world, Kyocera exports over 90% of their PV modules. Shares of 1991 worldwide PV production were almost entirely held by industrialized nations, with Japan, the U.S., Europe, and the rest of the world holding 36%, 31%, 24%, and 9% of production, respectively (Maycock).

What drives and accounts for the largest segment of this export market is developing country applications. Firor et al. (1993) conclude that although most *utility* involvement in PV systems has occurred in industrialized countries, the largest numbers of PV *systems* are in developing countries.

It is the intent of this paper to further explore the economics, sustainability, and dissemination process behind the promotion and adoption of PV technology in the developing world. The largest, fastest growing market for PV modules will not only impact the speed and success of electrification in developing countries, but will also influence renewable energy policy and research direction. The market demand for non-depletable, environmentally benign, energy sources will in the end depend upon both successful application in the field and successful cost reduction and technological improvements in the labs and factories.

II. THE DEVELOPING COUNTRY MARKET

During the 1970s, the notion of technology transfer of relatively sophisticated, untested, expensive technologies to nations with limited financial and technical resources was viewed more as political rhetoric than market viability. During the '80s, when governments relinquished as partners in research and development of renewable energy technologies, they remained as providers of aid to developing nations, and thus as an avenue for technology transfer and market creation. Agarwal et al. (1983) described the new attention to renewable energy technology transfer as a "supply push rather than a demand pull", significantly subsidizing the solar industry throughout the early '80s, and too often leaving the distant consumer without the technical or financial ability to apply and sustain the technology. They concluded:

> . . . most of these (renewable energy) systems were installed not because there was a local consumer demand for them but because a Northern entrepreneur was able to find a Northern aid agency to support their establishment as "demonstration" projects (Agarwal et al., 1983).

Today, PVs and other renewable energy technologies are widely promoted in developing countries, all before widespread use in the developed world. In many cases, PV dissemination has moved beyond the demonstration stage, and is spreading rapidly in remote power applications such as electric lighting, vaccine refrigeration, water pumping, and communications systems. System sizes vary from single-module lighting systems to larger water pumping or even village power systems.

The "Northern entrepreneur" and the "Northern aid agency" are still very much present. In some cases, developing country NGOs, technicians, balance of system suppliers, promoters, and importers have emerged, but the majority of projects have ties to foreign aid, assistance, direction, and products. U.S. based foreign aid donors for PV dissemination include the U.S. Department of Energy (DOE), the U.S. Agency for International Development (USAID), the World Bank, and the United Nations. The DOE has an international component of their research and development program. As chair of the Committee on Renewable Energy, Commerce and Trade, the DOE works in conjunction with 13 other federal agencies and the U.S. Export Council for Renewable Energy to promote renewable energy technology transfer (U.S. GAO, 1993). NGO and industry involvement with PV development work is even more extensive, often serving as promoter, financial intermediary, exporter, importer, consultant, installer, and/or parts supplier.

Renewable energy technology transfer, described as an industry scapegoat by Agarwal et al. in 1983, today is promoted on the basis of extensive rationale. Table 2 presents the most common.

TABLE 2
Typical Rationale for PV Promotion in Developing Countries

1. Large Percent of Population Without Electrical Service
2. Available Grid Power often Unreliable and Inefficient
3. High Solar Resource in many Developing Countries
4. PVs a Source of Decentralized Power
5. *Economically Competitive with Other Remote Power Options*
6. *Technologically Appropriate and Reliable*
7. *Positive Standard of Living Attainment*
8. *Environmental Benefits and Convenience*

Rationale 1-4 aren't particularly debatable. Rural populations throughout the developing world are without grid power, and the grid's extension has been slow in coming. For instance, in many African countries the percent of rural population with electricity service ranges between 0-5% (Hankins, 1993). When grid power is present, its availability can be highly unreliable and its delivery extremely inefficient. Thus, the decentralized, modular ability of PVs to provide power doesn't need to rely on extending grid lines. In addition, given the proximity to the equator of much of the developing world, the solar resource can be high and not as variable as locations closer to the poles.

The accuracy and motives behind the last four rationale are subject to debate and are addressed below.

III. SOLAR ECONOMICS

Before discussing solar economics with respect to current developing country applications, a note on much of the economic analysis to date is necessary to gain an understanding of some incorrect extrapolations to developing country projects.

Current PV costs are commonly published as low as 30¢ to 35¢ per kWh (SERI, 1990). These estimates are largely based on large-scale, electric utility experience with PVs in geographic areas with relatively high solar insolation (5 to 6 kWh/m^2) in which economies of scale, no power storage requirements, and considerable experience with electricity generation and cost control have played a significant role in maintaining low costs. Costs are also published in the form of \$/W or \$/m^2 but often with only the factory price of the PV module considered, excluding dealer markups, import tariffs, and balance of systems costs that can more than triple the initial capital outlay necessary for deliverance of power available for end uses. In addition, many system efficiency losses haven't been wholly accounted for in cost estimates, at times, accounting for more than a 20% cost oversight (explained below).

While utility PV experience is encouraging, using utility PV costs, or factory module costs, to infer costs of PV for small-scale, remote power uses is misleading. Clearly, the power storage requirements, efficiency losses, and small scale of stand-alone applications will impact the costs of electricity.

The following is an analysis of a one-panel PV lighting system as an example of small-scale PV costs in a remote setting. For comparison purposes, a small portable gas generator is also analyzed.

A. *PV Lighting System*

Recent PV projects have focused on providing minute levels of power generated at the household level, at times only enough to power a few lightbulbs. A recent study estimates that over 100,000 single module lighting systems have been installed in developing countries, or approximately 5 MW_p of cumulative installed capacity (Hankins, 1993).

PV lighting in the Dominican Republic (DR) provides an excellent example for further analysis. Erickson recently traveled to the Dominican Republic (DR) to investigate the PV dissemination process, the economic feasibility and sustainability of applications, and the characteristics of other sources of remote power. PV rural development has been present in the DR for nearly 10 years, initially promoted, and currently sustained through the efforts of Enersol Associates, a Massachusetts-based NGO. The Dominican Institute of Industrial Technology (INDOTEC) estimates that over 4,000 units have been installed to date (Rodriquez, 1993). Hankins (1993) estimates that the local PV industry includes more than ten installation businesses, two balance of system manufacturers, and four equipment importers (modules from Siemens, Solarex, Kyocera, and Hoxan). PV equipment and financial aid donors include: USAID, DOE, Catholic Relief Services, Siemens (formally ARCO), and Solarex. In addition, Enersol's model, the SOlar-BASed rural Electrification Concept (SOBASEC), has expanded to Honduras and has influenced PV projects in Sri Lanka, Kenya, Zimbabwe, China, and other developing countries. PVs in the DR have also played a role in stimulating the FINESSE program, initiated by the DOE and the World Bank to tackle financing obstacles of small-scale energy development.

Typical system costs are summarized in Table 3 by original or present value of capital, yearly and amortized costs, and cost per kilowatthour (kWh).[4] Most systems are sold and installed as a package including the panel, a control box, wiring, electric sockets, switches, and, usually, a battery. For instance, in the village of Los Aguitas, between 1989 and 1992, 48W systems (battery not included) sold for between 6,500 pesos and 10,000 pesos, or $530 and $810 at the current exchange rate of 12.35 pesos / US $. An analysis of an average system follows.

TABLE 3
Average PV Costs in the Dominican Republic

A. System Costs	Original or Present Value	$ / Year	$ / KWh (v)
PV Module, 48W (i)	450.24	73.27	0.951
Battery, 90 Amp (ii)	270.59	44.04	0.571
Charge Control Unit (iii)	40.00	6.51	0.084
Installation Labor (iv)	60.00	9.76	0.127
sub-TOTAL	820.83	133.59	1.73
B. Annual Costs			
(vi) Repairs	-	6.68	0.087
sub-TOTAL	-	6.68	0.087
C. Total System Cost	820.83	140.27	**1.820**
D. Household Equipment, DC (vii)			
Sockets, wiring, etc.	50.00	8.14	0.106
2 x Incandescent Bulbs, 15W	4.75	0.77	0.010
1 x Flourescent Lamp, 8W	2.43	0.40	0.005
12 inch B&W T.V., 14W	40.00	6.51	0.084
Radio, 14W	20.00	3.25	0.042
sub-TOTAL	117.18	19.07	0.247
E. Total Household Cost	938.01	159.34	2.067

See notes (i) - (vii) in text.

[4] Present value and amortization calculations are based on a discount rate of 10%, and an investment lifetime of 10 years. A sensitivity analysis to these assumptions is presented below.

i. PV module. Hankins (1993) estimates typical consumer module costs at $9.38/$W_p$. The PV module is the only imported component of the typical system. In the past, imports have been taxed at a minimum rate of 70% (Hansen and Martin, 1988). However, in May of 1988 a two year exoneration on duty was applied to PV and generator set imports, which was subsequently extended in December of 1990. PV panels are also installed in various watt sizes, ranging from 25 to 50 W_p.

ii. Battery. To store power for electricity use at night, low-performance, locally manufactured 12V car batteries are usually incorporated, at an average cost of $57. Replacement frequency can vary from 2-3 batteries in the first years, to average lifetimes of 1 to 2 years with careful monitoring (both Enersol Assoc. and Hankins [1993] confirm). The analysis assumes the battery is replaced every year and a half, but was observed to vary widely depending on battery, user experience, and financial ability to replace dead or damaged batteries.[5] Battery capacity ranges from 60 to 100 amp-hours; what might be used as a lawn tractor battery in the U.S. Imported, higher amp, longer-lived, deep cycle batteries are also available, although at significantly higher prices.

iii. Charge control. The charge control unit helps monitor the battery. They are assembled locally, encased in wood or metal plating, and contain a manually operated three-diode battery state-of-charge indicator, a system protection fuse, and at times a manual PV cut-off switch and a

[5] Automotive batteries are a familiar technology, used throughout the countryside for DC power and recharged at charging stations either by the grid or by gasoline generator. Carefully monitoring their charge is necessary to maintain the system. In particular, lead-acid car batteries are designed as starting batteries, which cycle only about 10% of their total capacity and recharge quickly from an alternator. Repetitive deep discharges, common in remote power uses, can damage the battery and affect its lifetime and charging efficiency. Used batteries are also utilized, reducing cost per battery, but decreasing lifetimes.

voltage converter for 9V radios. The single panel acts as a battery charger. As long as power is consumed and replaced regularly, providing a balancing load, then overcharging can be avoided and a more sophisticated charge control unit isn't necessary. Deep discharging is of most concern, and during periods of little sunlight, it is critical to moderate electrical consumption.

iv. Installation. Labor cost is estimated by Hankins (1993). Enersol trained, Dominican installers and/or their system installations were encountered in all the separate villages visited.

v. kWh production. Annual kWh production used in the denominator of the cost/kWh calculations is a function of average solar insolation, rated panel wattage, and system inefficiency losses. Daily solar insolation averages at 5.5 kWh/m^2 in the DR. The 48W PV system could provide approximately 264 W-hours/day, assuming no efficiency losses.[6] The significance of system power losses, however, merits further discussion.

Typical systems only have DC loads, although a few systems observed had small inverters (used to transform DC to AC power) and both DC and AC loads. Utilizing the power in its DC form cuts down on inverter losses, although electric line losses can be great if not properly installed. Considerable efficiency losses, however, occur in two other areas. First, the PV module itself is subject to module inefficiencies, dirt, and temperature-induced voltage drop - averaged as a 10% loss. Temperature can play a significant role, particularly in tropic climates. The wattage output of PVs

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[6] Available sun's energy is typically assumed at 1000W/m^2. Thus the kWh/m^2 solar insolation figure can be converted into a solar hour as an estimate of available energy. 5.5 solar hours times 48W yields 264 W-hours/day on average. Power will vary by the type of module and its respective efficiency in converting solar energy into electricity.

are typically tested and rated at 25° C, however modules usually run at over 40° C, and on very sunny, hot, windless days, as high as 76° C. Tested at 40° C, output drops to 94% of rated. Tested at 60° C, output drops to 87% of rated (Perez, 1992). In addition, extensive utility module testing programs found actual module power output to be generally 5 to 10 percent lower than the manufacturers claim (Firor et al., 1993). Real Goods Trading Corporation, a leading U.S. supplier of alternative energy systems, suggests a 15% PV de-rate factor when sizing a system to account for module losses, and de-rates higher than 30% when sizing a system in high temperature locations.

The second major area of system losses is in power storage and conversion. Charging efficiency varies by temperature, battery type, and age, but as a rule of thumb, every 1.0 amp-hour of AC current that is consumed, about 1.25 amp-hours of DC current is needed to replace it (Schaeffer, 1992). Since no inverter is required with DC loads, the battery inefficiency factor was scaled back to 10%.

In the end, a 20% inefficiency de-rate was used, translating into 211.2 W-hours/day (77.1 kWh/year) of usable power. Much higher inefficiencies could occur given the low-performance batteries used and frequency of high temperatures; i.e., 20% is taken as a minimum.

vi. Repairs. Annual repairs were calculated as 5% of the yearly generator cost sub-total. The most common repairs are blown fuses often due to short-circuits caused by rats eating wire (Hansen and Martin, 1988) or exceedingly heavy electric loads. Broken light switches, filling batteries with distilled water, terminal cleaning, battery disposal, new wiring, and general panel care, are also included in repairs.

vii. Household power consumption. Under household equipment, Table 3 lists a typical consumption load, given a 48W panel. An average of

211.2 W-hours/day of usable power (20% inefficiency loss), during an average 24 hour period, could power two 15W incandescent bulbs for 2 hours, an 8W fluorescent lamp for 5 hours, a 14W black and white television for 3 hours, and a 14W radio for 5 hours. The incandescent bulbs and the fluorescent lamp's lifetimes average 1000 hours and 9000 hours, requiring replacement every year and a half and every five years on average, respectively.

Given a 12 volt system, this consumption translates into 17.66 Amp-hours/day. A fully charged 90 amp-hour battery could provide enough power for 4 days of the above consumption before reaching an 80% critical discharge level. If deep battery discharges were common, particularly with a low-performance lead-acid battery, batteries would most likely have to be fully recharged off the grid, charged from the PV panel over a period of no power consumption, or risk failure.[7]

The household consumption load in Table 3 can vary by appliance, wattage, and hourly use. Five watt incandescent bulbs and 6W motorcycle tail lamps are also common to DR systems.

B. *Portable Gas Generator*

Gasoline or diesel generators are a common source of remote or back-up power throughout the world. In the U.S., the Environmental Protection Agency estimated in 1990 that 51,344 units less than 25 horsepower were operating (U.S. EPA, 1991). In the Dominican Republic, many of the hotels, stores, restaurants, and other commercial operations

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[7] Hansen and Martin (1988) recognize dead batteries as a common system failure, "caused by normal battery deterioration or, in new systems, by the users' overconsumption of electricity". In Erickson's observations, dead or severely discharged batteries were encountered, particularly when used batteries were purchased.

either have their own generator or are connected to a central, commercial generator for the purposes of daily backup power from the national grid. Some remote locations have large village generators, but their dissemination is tied to the government run utility and has been slow to spread. Portable generators, however, are a source of household power with similar up-front costs as a PV system. Even the smallest generators (650 - 1100W) supply between 13 and 22 times the rated wattage of a 48W PV panel. The advantage in cost/kWh is outlined in Table 4, and an analysis follows.

TABLE 4

Portable Generator with PV Household Consumption

A. System Costs	Original or Present Value	$ / Year	$ /KWh (iii)
Honda 650W Portable Gen. (i)	519.00	84.46	0.068
Installation / Accessories (ii)	40.00	6.51	0.005
sub-TOTAL	559.00	90.97	0.073
B. Annual Cost (iv)			
Fuel (60% tax)	-	423.98	0.342
Oil	-	40.00	0.032
Repairs	-	9.10	0.007
sub-TOTAL	-	473.08	0.382
C. Total System Cost	559.00	564.06	**0.455**
D. Household Equipment, AC (v)			
Sockets, wiring, etc.	50.00	8.14	0.007
2 x Incandescent Bulbs, 15W	4.75	0.77	0.001
1 x Flourescent Lamp, 8W	2.43	0.40	0.000
12 inch B&W T.V., 14W	40.00	6.51	0.005
Radio, 14W	20.00	3.25	0.003
sub-TOTAL	117.18	19.07	0.015
E. Total Household Cost	676.18	583.13	0.470

See notes (i) - (v) in text.

i. Portable generator. The cost of the generator will vary depending on taxes, dealer markups, or brand name. The 650W generator is the second smallest generator Honda makes, and the one assumed above is the middle-line model at that wattage. The model is designed for long-running, with the option of running 120V, 650W max. (5.4A) AC power and 12V, 100W max. (8.3A) DC power either separately or simultaneously.

ii. Installation. Installation is minimum given the portable nature of small generators. Accessories might include a small storage area, extra gasoline tank, safety disconnect, fuse box, and possibly a junction box if more than one household was involved.

iii. kWh production. The efficiency of a Honda generator is considered very high, with regular oil changes and cleaning, and an inefficiency adjustment is taken as a maximum loss of 5%. To compare to the 5.5 solar hours in the PV case, the generator is assumed to run 5.5 hours/day. At 95% of rated power, this supplies 3,396 W-hours/day (compared to 211 W-hours/day in the PV case); or 1,240 kWh/year used in the denominator of the cost/kWh calculations.

iv. Fuel, oil, and repairs. Operational capacity on one tankful of gas (0.7 gallons) is rated at 5.3 hours. The major current effect on fuel prices is taxes. In the DR, gas price is currently 20 pesos/gallon (or U.S. $1.61), up from 12 pesos/gallon in 1990. In our analysis, the base cost of gas is taken as $1/gal, with a 60% fuel tax added. Oil must be changed every 1-2 weeks. Repairs might include cleaning and lubrication, as well as spark plugs and fan belt replacements, and are charged as 10% of the amortized cost of the generator.

v. Household power consumption. The 650W generator can power significantly higher wattage bulbs and appliances, all with AC power. For comparison purposes, the same household equipment is included; although their operational time is only restricted to the run time of the generator, not the charge of a battery. At peak consumption of 66W (all lights, T.V., and radio operating), only 11% of the generator's output is being utilized. An additional 8 identical household consumptions could be added to the system.

As with the PV system, type, wattage, and number of electric loads can be varied, but the generator offers considerably more flexibility. The same generator with an electric start, could run a small 140W refrigerator/ freezer, a small 100W water pump, six 15W fluorescent lamps (60W incandescent lighting equivalent), a 60W color T.V., a 15W stereo, and varying "quick consumption" devices such as a blender, toaster, frying pan, iron, and/or sewing machine. Such a load might use an average of 8 hours/day run time costing $50/month in gasoline at about $0.40/kWh. If a PV system was assembled to match the wattage of the generator using ten 64W panels, the panels alone would cost over $4500, and total system costs would fall only to $1.30/kWh.

Although not the most efficient way to use a generator, batteries could be charged from a generator using a battery charger to capture the full 650W, or directly from the 100W DC output. Perhaps to keep fuel costs down, the generator could power AC loads in the daytime while charging a battery for nighttime lighting and entertainment.

Generators are also used at charging stations to charge batteries. At a Texaco station in San Jose de Ocoa (DR), a small Kawasaki generator was charging a battery, costing about 5 to 10 pesos per charge (U.S. $0.40 to $0.81). Many of the villagers without PV, grid, or generator power are utilizing car batteries to run T.V. and radios, recharging at a station every 6 to 8 days.

C. *Sensitivity Analysis*

The DR is one of many developing countries where PVs are being actively promoted. System components, solar resources, and consumption makeup will vary, depending upon who is promoting a system and where. British Petroleum (BP) has a solar division that markets solar lighting kits throughout Africa and Asia. A 40W panel kit sells for $580 (not including battery, import taxes, or installation) and comes pre-wired with an assembly and instruction manual. In Zimbabwe, various dealers market similar one-panel systems for between $700 and $2000 (Hankins, 1993), significantly increasing the system cost per kWh estimated in the DR case.

To investigate the sensitivity of the generator/PV comparison it is necessary to vary the assumptions, including capital costs, solar insolation, fuel tax, discount rate, and investment lifetime. First, the amount of daily solar insolation will significantly affect the cost of PV power, and will depend on geographic location and frequency of weather events (i.e. cloudy periods). Figure 1 demonstrates the effect on power cost when the solar insolation and capital costs are varied. For Kenya, the average cost of a module, 90A battery, charge control unit, and installation, are \$7.80/W_p, \$106, \$83, and \$65, respectively. In Zimbabwe. the same costs are \$14.34/W_p, \$53, \$11.40, and \$60, respectively (based on Hankins, 1993). The arrowheads in Figure 1 point to the average system cost for the three countries given their average solar insolation in each capital city.

In the generator case, the level of total fuel tax will have the largest effect on power cost. Figure 2 shows the results of varying the tax on gas

Figure 1. Sensitivity of Solar Insolation and Capital Cost Assumptions

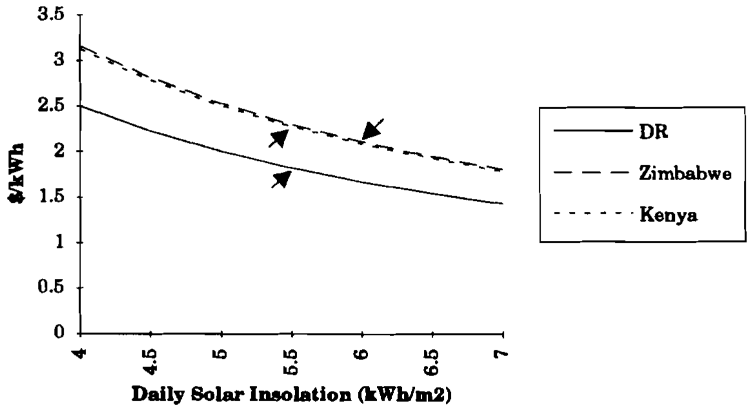


Figure 2. Sensitivity of Fuel Tax Assumption

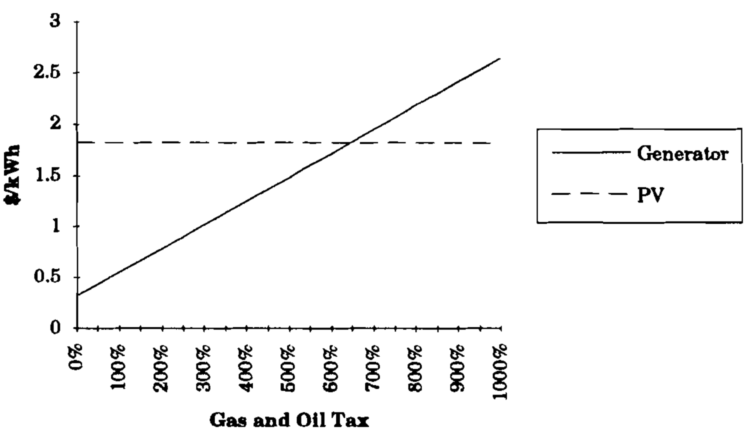
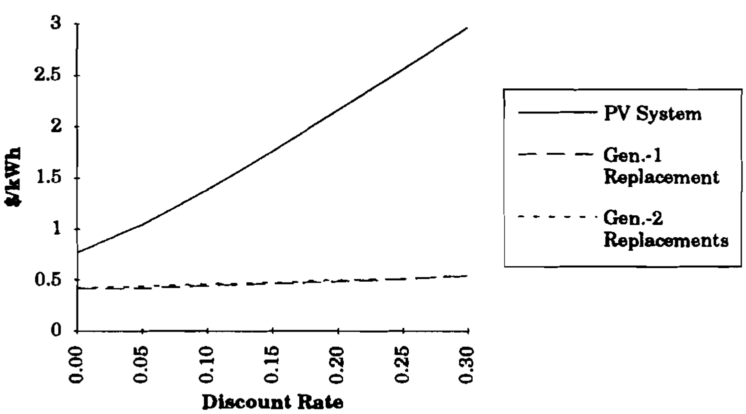


Figure 3. Sensitivity of Discount Rate with 30 Year Investment Period Assumed



and oil, and holding all other assumptions from Table 4 constant. The average PV system cost in the DR of $1.82/kWh doesn't become cost competitive until a fuel tax of over 650% is levied. Bear in mind, the 650W generator is one of the smaller portable generators available. A 2200W Honda portable generator is available for an additional $300 (Schaeffer, 1992).

A third set of assumptions that can be varied are the discount rate and the comparable system lifetimes. Based on the information from Tables 3 and 4, Figure 3 shows the effect of varying the discount rate on system costs, assuming a 30 year lifetime for the PV panel and both a 15 year and 10 year lifetime for the generator. The cost of the generator varies little when its lifetime is decreased 5 years due to the fact that fuel cost makes up the most significant lifetime expense. Different discount rates would be justified for different circumstances. For instance in the village of Los Uberos in the DR, loans for 25W system were being issued on 18% annual interest terms.

It is difficult to imagine a case where the PV system would be economically competitive given current system costs, inefficiencies, and technology.

IV. THOUGHTS ON TECHNOLOGY, STANDARDS OF LIVING, AND ENVIRONMENTAL BENEFITS

The economic comparison in the previous section is not meant as a justification for promotion and financing of portable generators throughout the developing world. Rather, the comparison demonstrates that the photovoltaic technology being actively promoted and financed in the

Dominican Republic, and countless other low-income nations, is far from economically competitive with traditional energy technologies.

The rationale for visiting the Dominican Republic was to explore beyond the economic comparisons and ask: what drives the PV dissemination process; are PVs a reliable and sustainable source of remote power; and, does PV promotion make sense for other reasons? Aside from $/kWh comparisons, PVs have been promoted on the basis of their noise-, maintenance-, gas-, and pollution-free characteristics. Generators are noisy, maintenance can be extensive (i.e. village power systems), fuel is required regularly, and air pollution from gas combustion includes nitrous oxides and hydrocarbons (precursors to tropospheric ozone [smog]), and carbon dioxide (the chief greenhouse gas).

A. *Noise and Maintenance*

The power of a generator can make up for its hum. If the option was presented to have a noisy 650W generator that could provide over 13 times the power of a 48W PV panel - on demand, opening up numerous electricity consumption options and standard of living attainment, all at a significantly cheaper cost of power - the quiet of a PV panel might not be valued as high. Current models are sold that have reduced the noise to a low hum.

Maintenance is a real concern, but a familiar one. Combustion engine technology has been present in the developing world for a long time. In the DR, although many of the PV powered villagers are far from the beaten path, motorcycles and some automobiles are very common. Although village generators present bureaucratic and more larger-scale maintenance problems, portable generators are relatively simple and maintenance free as long as basic care is taken. Two Honda generators were seen in the DR, being used for remote power for a number of years without any difficulties, and powering 60W bulbs and higher wattage appliances.

The maintenance of a PV system isn't as "free" as it might seem. There are no moving parts involved in PV electricity, however the storage of power presents significant difficulties. Car batteries in particular aren't designed to handle frequent deep discharges. In San Jose de Ocoa in the DR, PV users had replaced their batteries two or three times during their first years of operation. The users also had grid power (although extremely unreliable) and were inexperienced with carefully monitoring electricity consumption. In Los Aguitas, a few of the villagers couldn't afford to buy new batteries and opted for used ones, all of which lasted from 3 to 5 months.

Blown fuses and broken light switches were also described by the villagers as common problems, with small replacement expenses when parts were available. A few households were turning lights on and off by making the wire connection by hand. Burned out lightbulbs were rarely encountered, the charge control boxes all appeared to being functioning well, and household wiring was simple and neat.

B. *Fuel*

Perhaps the regular expense, burden of transport, and availability of fuel presents the strongest argument against using traditional fossil fueled power for household rural electrification. However, in most developing countries, when the world supply of oil is steady and domestic demand is present, gasoline is plentiful. In addition, rural communities regularly transport gas from stations by whatever means necessary. In the DR, motorcycles with gas jugs tied to their sides were seen and the PV promoter in San Jose de Ocoa also made a living by transporting gas in his 4 x 4 vehicle to remote households with generators.

The argument of fuel expense has mixed validation. In the generator case in Table 4, fuel costs approximately $35 per month. On a $/kWh basis this cost is very low. However, to a household using only 11% of the generators capacity, this cost can be prohibitively expensive. PVs have the advantage of paying for 20 to 30 years of power production up-front. To the community of Los Aguitas, this factor motivated two families to sell their generators to someone in the city and purchase a PV system. It is interesting to note that no development organization, financing, or influence was present, and they heard of PV on a radio advertisement from a Dominican entrepreneur.

The economic rationale behind these decisions was two-fold. This area of the country made the majority of their living as tobacco farmers. Their monthly income was highly erratic, and to them it made sense to pay for a PV system up-front when they had extra money from a good harvest or sent from a family member abroad, rather than worry about supplying fuel on a monthly, and therefore, unpredictable manner. This same variance in income, however, has hampered some households from affording replacement batteries for extended periods of time, rendering the PV system useless for nighttime electricity.

The macroeconomic setting of the DR also influenced this community's decision to invest in PV systems. The DR has experienced periodic gas shortages (the last ones in 1990 and 1986) apparently because of problems with government oil contract obligations, and shortage of storage capacity. These have left the rural communities without access to gas for transport or power for extended periods of time. In such a climate, the $/kWh economic advantage is less important.

C. *Power Demand*

PV justification has also been grounded in an argument for meeting minute power demands with minute power loads. This argument ignores the fact that if more power is available, particularly at a cheaper cost, more consumption may arise. In the area of Bella Vista, the village where Enersol and its Dominican counterpart is based out of, the grid has recently been extended further up the main road. Houses that were previously powered solely by PV have opted to pay for grid connection (about 500 pesos or US $40). With grid power, a family had an ice box, an iron, 60W lights, T.V., and radio, and was paying about 60 to 70 pesos/month (US $4.85-5.67). In Los Aguitas, a man across the road from a PV powered house had bought a 1000W Honda generator for 300 pesos less than the family with the 48W PV system. The family with the PV system had a leaking battery that was dead and couldn't afford a replacement at 600 to 800 pesos (US $48-65). The man with the generator operated a dancing/cock fighting establishment, and powered high wattage bulbs and radio.

In general, the generator or grid (when available) offers a cheaper cost of power and can free up resources for more power consumption and greater increases in standard of living.

D. *PV Development and the Environment*

It should be emphasized that the more successful PV applications encountered in the DR were without the presence of development aid financing. In the village of San Jose de Ocoa, where the majority of systems were bought on credit from a Catholic Relief Service fund, many systems were having problems. It seemed most people, after paying a down payment, were not paying monthly for their systems. The presence of financing for PVs over generators had significantly influenced the choice of technology. The PV promoter in San Jose de Ocoa said that financing wasn't available for generators, a power source that he felt was cheaper, familiar, and more reliable.

It is difficult to apply field experience in one developing country as a general conclusion for PV technology transfer as a whole. It is clear that this subsidized PV dissemination and influence on technological choice is what is gaining attention throughout the developing world as an investment for development aid dollars, which introduces the last rationale for PVs: environmental.

Concerns such as global climate change and associated pressures on environmental technology transfer, have thrust PVs into the international policy arena. The Global Environmental Facility (1992) is investing $7 million in Zimbabwe for PV rural electrification, with the expressed purpose of offsetting carbon dioxide (CO_2) emissions growth. The DOE is sharing the cost of a $1.4 million PV lighting project in Brazil, where 800 U.S. made systems will be installed, partly for the purpose of displacing diesel fuel use (Public Power Weekly, 1993a). The World Bank is providing a $55 million dollar loan for similar PV development in India (Asia Alternative Energy Unit, 1993).

PVs and other renewable energy technologies will be required to move into an era of sustainable development and to avoid costly environmental externalities associated with past development. However, it is doubtful that developing countries can significantly increase their needed energy resources on currently uneconomical, donor supported technologies. The entire industrialized world developed largely from burning cheap fossil fuels, and it would seem the developing world would also require access to inexpensive energy supplies to fuel their economic development. Developing on renewable energy before economical and sustainable applications have developed, will likely result in minor, short-run development at major international aid costs, while ignoring the central issues of more research and development into renewable energy systems.

Attention to premature PV technology transfer also neglects the substantial greenhouse gas reductions and other environmental benefits that can occur through energy efficiency and conservation efforts throughout the world. Available technologies and policies can reduce energy consumption at a negative net cost, offsetting negative environmental externalities in areas such as rural development (see Drennen, Erickson, and Chapman, 1993).

V. CONCLUSIONS

A recent U.S. General Accounting Office report (U.S. GAO, 1993) addressing the development of solar and wind energy, concluded that the number one opportunity in renewable energy development was additional funding for research and development (R&D) aimed at lowering costs. The GAO described the differences in cost of power between traditional sources and solar and wind sources as partly due to the missing cost reflection of negative externalities from nuclear and fossil fuel use, and partly "the effects of past research and development funding allocations and tax benefits that were directed more toward conventional, nonrenewable energy sources."

The American Solar Energy Society estimates the externality cost of conventional energy technologies to be $0.02/kWh (Larson et al., 1992). These costs are based on U.S. energy consumption and include costs due to corrosion, crop loss, health impacts, radioactive waste, military subsidies, and jobs lost. Even if the cost of other negative externalities, such as global climate change, were to triple or quadruple this estimate, the current difference between PV (small-scale or large-scale) and fossil fuel power costs would remain significant (see Drennen, Erickson, and Chapman, 1993, for a more detailed discussion).

The preference in energy research allocations is obvious. Over the past 20 years, the DOE has invested more than twice as much into the development of fossil fuels, and nearly four times as much into the development of nuclear energy, than it has invested in development of all renewable energy technologies combined - including solar, wind, biofuel, and ocean. In 1993, the DOE is budgeted for $306.8 million in nuclear power and waste research, while not one U.S. order for a nuclear power plant has been placed in over 15 years. In comparison, total renewable energy research was allocated $187.4 million (U.S. GAO, 1993). Research priorities must change.

Advocates of PV technology transfer, however, contend that PVs are economically competitive now, requiring no further R&D, and that further *market* development will bring costs down for a wider range of applications (Caldwell, 1993; Williams, 1992). Observing cost/kWh comparisons, PVs are clearly not competitive with fossil fuel power, and contrary to the market development hypothesis, world PV production has more than doubled in the last seven years while average factory prices of panels have yet to break the $\$5/W_p$ barrier set in the mid-'80s.

Much of the PV production expansion in developed countries has been consumed through export to developing countries. Consequently, the export market has the most potential to distort R&D priorities. The preceding analysis contends that even under the most favorable conditions of higher fuel taxes, 0% interest rates, and 30-year panel lifetimes, PV systems in developing countries are still noncompetitive with gasoline-powered electric generators. While there may be circumstances when PVs are chosen over traditional forms of remote power, the decision to install PV systems in developing countries has been heavily influenced by international aid organizations, at times with ulterior motives involved (i.e. environmental, market expansion).

PV research currently has a mix of strategies: one favoring further market development and subsidized export, and one favoring a return to federally funded and directed R&D. Our conclusion is that in order for PVs to become competitive with fossil fuel technology, overall system costs must drop, and system efficiencies must increase; a return to DOE goals of the 1970s. This entails technology and manufacturing research on PV modules and balance of system components, i.e., power storage and conversion.

In the U.S., DOE funding for renewable energy development has recently been on the rise. The 1994 R&D request is $327 million, 74% over 1993 allocations (Public Power Weekly, 1993b). The key for renewables in general, and PVs in particular, is to direct this money towards a R&D strategy rather than a market-push strategy. Current industry-government programs can quickly benefit from additional financial resources and federal priority. For example, the 5-year, $55 million, PV Manufacturing Technology (PVMaT) project is viewed as a renewed government-industry cooperative approach to improving manufacturing and reducing costs (NREL, 1992).

By far the most under-utilized resource in current renewable energy research are universities. The DOE's Office of Energy Research provided $2 million to the National Renewable Energy Laboratory (then the Solar Energy Research Institute) in 1990, of which 0% was allocated for their university research support program (SERI, 1990). Universities not only provide a medium for technology R&D, but educate our future scientists and policy-makers.

In summary, the path towards a renewable energy future entails a realistic assessment of current costs and a firm commitment to research and development. Current international aid subsidies for PV technology transfer to developing countries may have the unfortunate consequence of drawing attention and resources away from necessary research. In addition, the high cost and low power of PV applications are resulting in slow, and possibly unsustainable, development at comparably high international aid costs. Goals of environmentally-wise energy development can be obtained through addressing energy efficiency and conservation in the near-term, while focusing on bringing PV costs down for future, economically competitive applications.

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