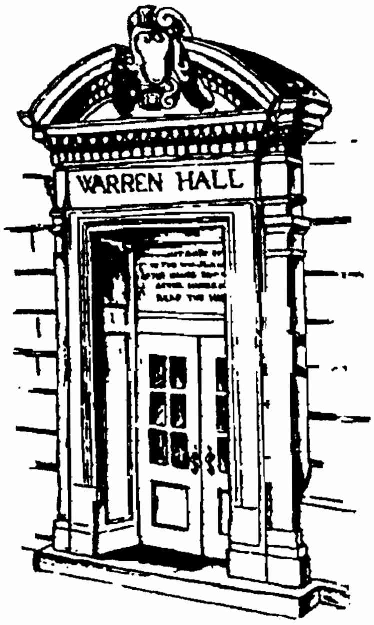
WP 94-03
February 1994



Working Paper

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ECONOMIC EVALUATION OF RESIDENTIAL SOLAR ELECTRICITY IN DEVELOPING COUNTRIES

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February 17, 1994

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1. Introduction

In this paper our purpose is to understand the current market conditions that influence the adoption and maintenance of solar energy systems. The motivation arises because renewable solar energy may offer a different route to higher living standards for developing countries than the path followed by industrialized countries. If this is feasible, then accelerating use of energy in developing countries need not be accompanied by accelerating releases of carbon dioxide, the major greenhouse gas. Similarly, providing for developing country electrification through solar energy would reduce the growth in regional air pollution such as ozone, carbon monoxide, acid deposition, and particulates.

The decision to focus on household PV (photovoltaic) systems is based upon several considerations. Admittedly, there are other solar technologies in use today, for example, household hot water systems and central station thermal systems (see Johansson et al., 1993 for a current summary). In addition, solar energy may be defined as renewable energy, in the sense that biomass energy and hydro and wind power originate with solar-driven atmospheric forces. However, amongst the renewable technologies being emphasized as appropriate for developing countries, household PV electricity is the leading technology. Furthermore, PVs have, currently and in the past, claimed the largest share of U.S. federal appropriations for renewable energy activities (Golub and Brus, 1993). In the U.S. as well as in developing countries, PVs are beginning to penetrate markets accessible to PV's major competing technology, portable generators. In the U.S., capacity for remote household PV installations is now about 20 MW (megawatts), equal to 7% of the small generator capacity (U.S. EPA, 1991; U.S. GAO, 1993). For a comparative perspective, utility generating capacity in the U.S. is 700,000 MW (Electric Power Monthly 8/93).

2. Scale Economy and Technological Innovation

Economic logic implies that, in terms of optimal public policy, the implementation of solar PV technology should be promoted in the time period wherein the declining social cost of PV energy passes below the rising social cost of conventional energy generation. Given the presumption that social non-market cost of gasoline production and use is significantly greater than that for PV use, it should be expected that private market outcomes would defer solar implementation to later periods than would be socially optimal.

With respect to producer costs for PV installation, it is widely believed that significant scale economies reduce marginal and average cost as installations and capacity increase.

Figure 1 shows a highly simplified static representation of these assumptions. Three curves are shown. Demand for solar of course increases with a lower price; the arrow also shows solar demand shifting up as conventional energy prices and taxation rise over time. The marginal market cost curve for solar (MMCs) shows scale economy, with marginal cost declining as volume increases. The arrow represents two dynamic factors which shift the MMCs curve downward. These two factors are (a) the learning curve effect, over time, and (b) the beneficial results of public investment in solar research.

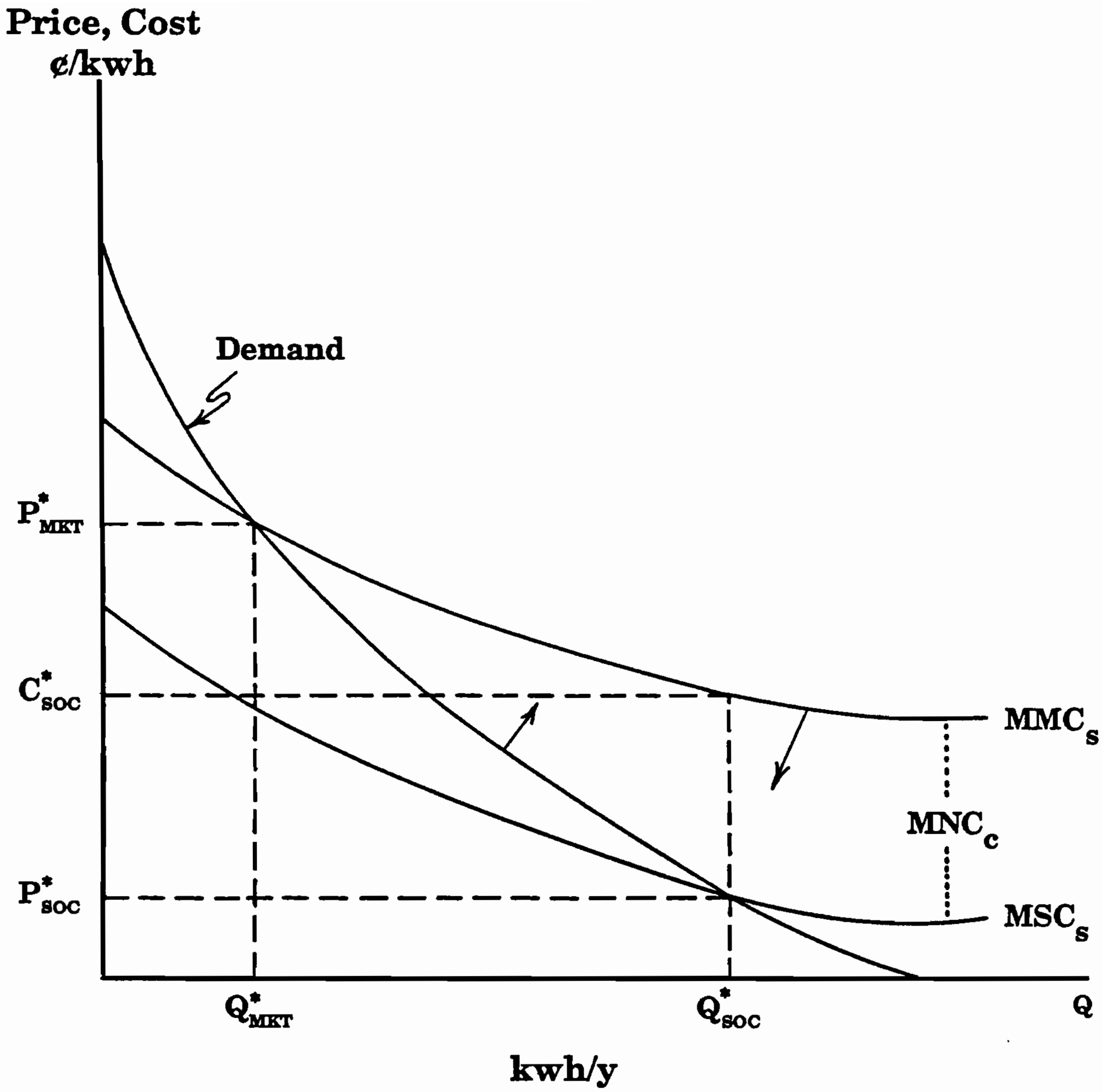


Figure 1. Simplified Solar Market

The marginal social cost of solar (MSCs) is represented in the Figure as a constant distance below MMCs. This constant distance is a simplified assumption: the marginal non-market environmental cost of conventional electricity (MNCc) is constant, and each solar kilowatt hour displaces a conventional kilowatt hour. Therefore, under this representation, the social cost of solar electricity is less than the market cost by the value of the non-market environmental cost of the displaced conventional electricity.

The market outcome in the Figure (P^*_{MKT}, Q^*_{MKT}) shows high price and cost for household PV, and low sales. However, the social optimum is a much higher quantity, Q^*_{SOC}. In order to attain this social optimum quantity, government must subsidize the market price at P^*_{SOC}. The total subsidy in dollars is equal to the box with length Q^*_{SOC} and width C^*_{SOC} - P^*_{SOC}.

In summary, the hypothesized joint existence of significant scale economies by producers as well as external social benefit from solar electricity use combine to offer strong economic incentive for developmental subsidy of PV use. Under these conditions, government and donor aid support clearly promote economic efficiency.

The next section addresses a set of narrow but important parts of the problem: the current market costs of conventional and solar remote household energy, technological gains, and estimates of non-market environmental cost of conventional energy use.

3. Economic Analysis and External Costs

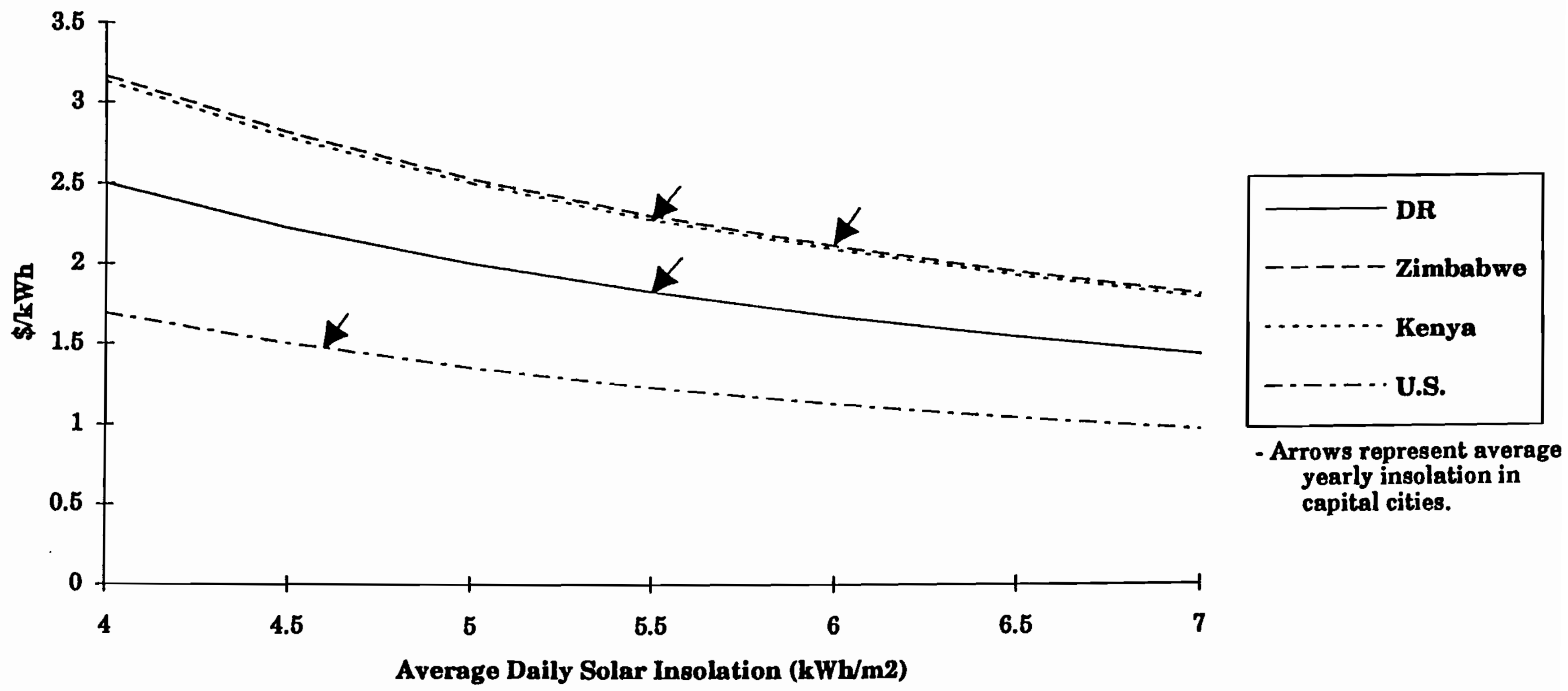
With smoothly functioning world markets, the pre-tax cost of electricity from portable generators would be fairly uniform throughout the world. Transportation of generators to and within developing countries would be similar everywhere: a 500 Watt generator shipped from Japan to New Mexico would have transport cost comparable to a generator shipped to the Dominican Republic or Africa. Similarly, the production cost of gasoline should be nearly identical: a Shell refinery in Durban can use the same technology as a Shell Caribbean refinery, and the transport cost of crude oil and products is only a few pennies per gallon (Chapman, 1983, p. 126). The basic costs of installation for solar systems should, in the same way, be similar throughout the world in locations near major transportation systems.

In defining maximum energy production from a given site, a solar system is site-specific in that its electricity production is affected by the incidence of solar insolation. In Ithaca, New York insolation averages only 4 kWh per square meter per day. In contrast, Arizona reaches an annual average of 7 $kWh/m^2/d$. Most locations are between these values; Zimbabwe sites, for example, receive an average of about 6 $kWh/m^2/d$. This means that the insolation factor alone reduces kWh costs by 43% between Ithaca and Arizona. Zimbabwe, other things being equal, would be 17% more costly than Arizona.

Usable solar electricity is also influenced by battery storage and the capability of transferring electrical energy from the period of solar generation to periods of nighttime or cloudy day use.

The unsubsidized, untaxed market cost of imported PV systems should, as with portable generators, be similar for developing country and U.S. locations with equivalent solar insolation. However, as Figure 2 indicates, actual cost curves are not similar. The Figure shows the full cost of a 48 Watt system in three developing countries and in the United States (U.S. Prices: Real Goods, 1992). The methodology is summarized in the Appendix, Part A. The curves

FIGURE 2. Solar Insolation and Cost: Four Countries



show declining cost as insolation increases, and the arrow shows average annual insolation for each country. The sources of data for developing countries are Hankins, and field trips to Zimbabwe and the Dominican Republic by Agras and Erickson (Erickson and Chapman, 1993; Erickson, 1993; Hankins, 1993; Agras, 1993). For this modest capacity (48 Watts, 77 kWh/y in Zimbabwe), panel investment cost is 60% of annual equivalent cost per kWh.

While portable generators now exhibit less cost per kWh than PV systems for well-functioning markets, it should not be assumed that PV will never be chosen. Three factors favor PV systems. First, a PV system is available at a lower capacity, and, at a modest cost for lights, radio, or television, the system can be fully utilized by a household. An under-utilized portable generator may have kWh costs comparable to those of the PV system. (Note the section of Figure 3 to the left of 168 kWh/y that shows this.)

A second factor favoring household preference for PV is the absence of the noise and smell of generator operation. Finally, an inefficient parastatal petroleum company or national government may be so unreliable as to lead a household to feel more secure with PV because gasoline may be unpredictably unavailable.

Current estimates of the environmental and health damage from power generation vary. The American Solar Energy Society reported an aggregate estimate of 2¢/kWh (Dec. 1992, p. 30). Hall's figures (1992, p. 491) for coal, petroleum, and natural gas are in Table 1. When viewed as energy sources for power generation, they range from 3¢/kWh for coal to 6¢/kWh for petroleum. The Hall figures are based upon estimates of national security costs and environmental damage.

FIGURE 3. Cost at Very Low Energy Levels

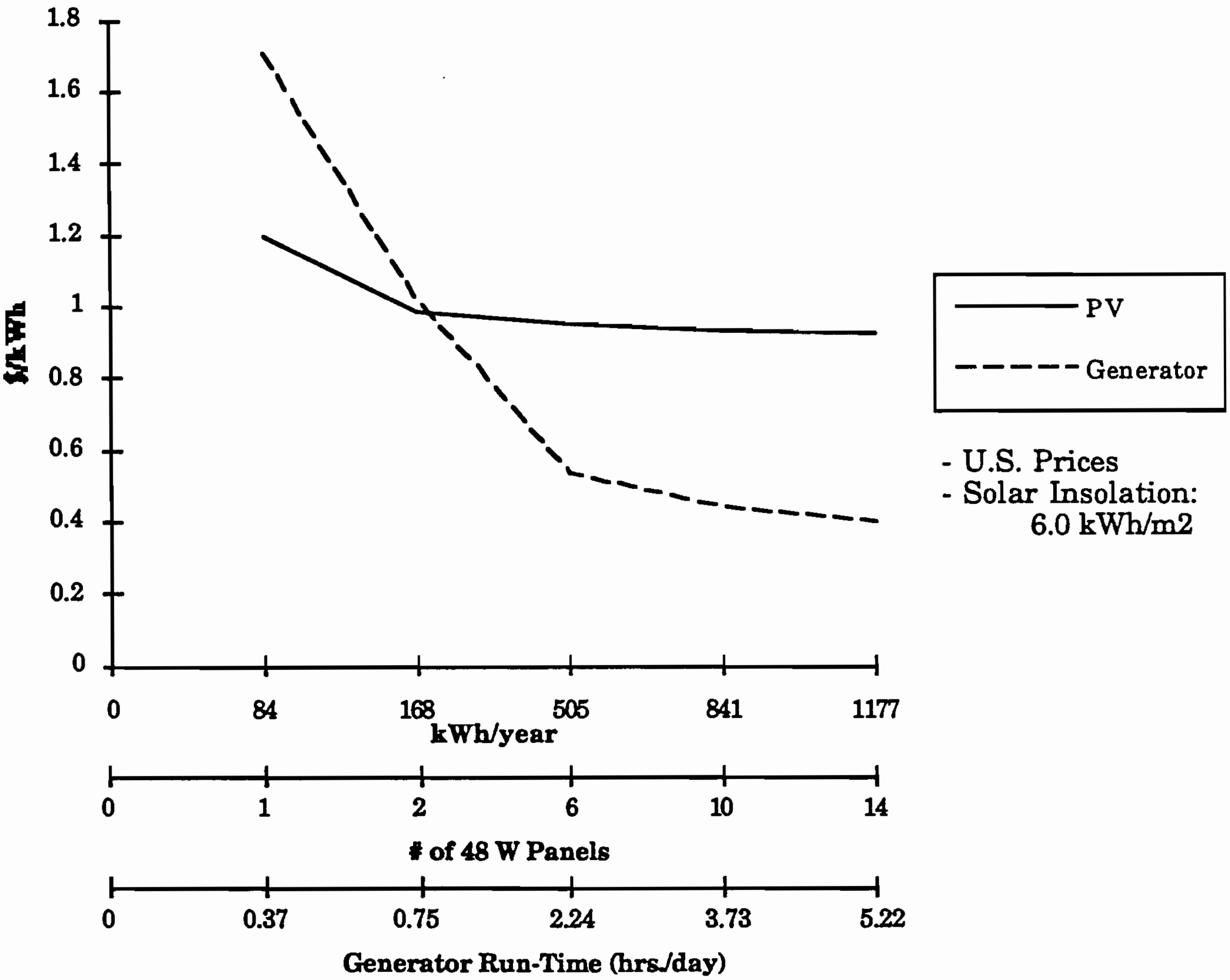


Table 1. Hall's External Social Costs

Fuel Type	Hall, External Social Cost	Calculated Social Cost per kWh
Coal	$54/ton	2.7¢
Petroleum	$35/barrel	5.8¢
Natural Gas	$3.05/mBtu	3.3¢

Sources: Hall (1992), Monthly Energy Review (1993)

Social cost can be defined as the sum of external social cost plus private market cost. Even, with this assumption, however, the marginal social cost curve for PV remains above the social cost curve for conventional energy. This is, in fact, the basis for the configuration of the social and market cost and demand curves in Figure 1 in the Introduction. While the Table 1 values are very significant proportions of central station electricity cost, they are not sufficient to alter the basic PV and portable generator comparison.

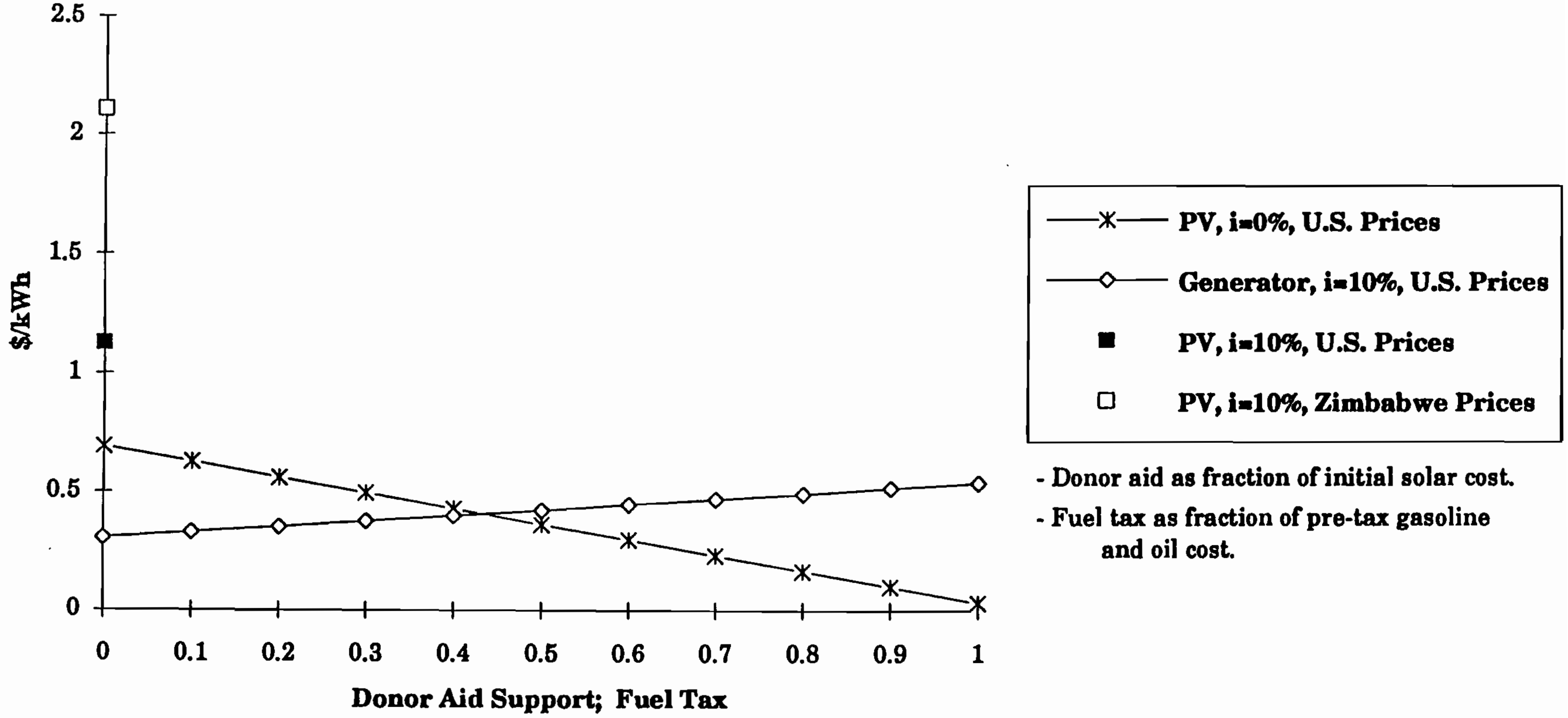
4. Gasoline Taxes; Donor Aid; Policy

Greater penetration of remote rural markets can be achieved by donor aid that reduces initial PV cost, or reduces the interest charges on PV loans. Figure 4 shows the effect of reducing interest on a PV loan from 10% to 0%. This is represented by the movement down the vertical axis from the dark box at $1.12/kWh and 10% interest to 70¢/kWh with an interest-free loan (at the "x"). The declining "x" line in the Figure shows the continuing reduction in cost associated with increasing amounts of donor aid.

The open diamond line represents portable generator cost per kWh increasing as fuel tax rises. Note that a combination of an interest-free solar loan and 50% donor aid coupled with a 50% gasoline tax would give PV a slight edge in efficient markets.

In reality, donor aid does not always lower the solar cost curve. In one country that was analyzed extensively through field research of local installations, PV fabrication is supported by a network of international donors supplying materials, technical assistance, large scale promotion, and low interest loans. The donor aid is probably some multiple of the cost

FIGURE 4. PV vs. Portable Generator Costs varying Interest Rate, Donor Aid Support, and Fuel Tax.



charged to PV users. Nevertheless, the cost to users appears higher than it might be in the absence of international donor aid in an efficient market.

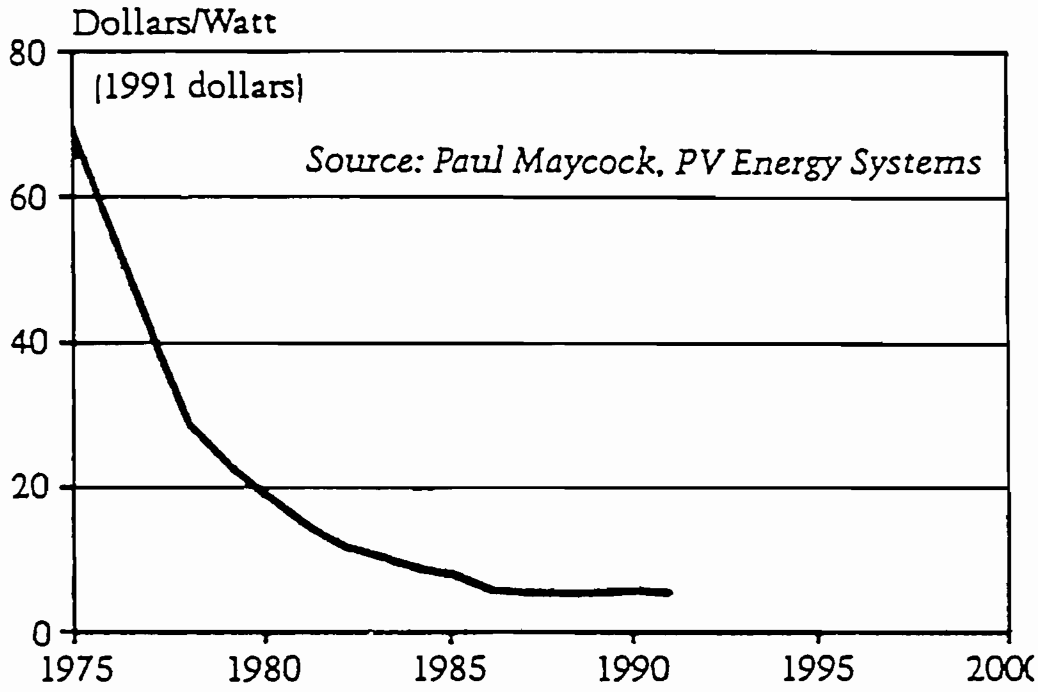
In another small, developing country, the continued use of PV systems depends upon the dedicated commitment of one expatriate with a high level of technical and marketing skills. This individual is supported by international aid.

Technological complexity may not be a major factor in the choice. A household with the expertise to wire and operate home electricity can handle PV or portable generators with equal facility. Field research suggests that components for both systems are usually equally available in countries with PV use (Agras, 1993; Erickson, 1993). In one region in the Dominican Republic, the same individual that delivers gasoline for household portable generators also sells and maintains household PV systems.

Given the apparent importance in the near term of donor aid support for developing country applications, the question arises as to the best allocation of solar R&D. Is the return greater for a dollar invested in a university laboratory on basic research, or for a dollar invested in placing a solar unit with a rural developing country business or household?

Figure 5 is a representation of the decline in PV costs over time. It is primarily the learning curve effect. It shows falling cost per kWh, but the rate of reduction is declining. This reduction in market cost is a reflection of a major basic research effort in the 1970s and early 1980s. This university-industry government program reduced panel costs from $75 to $5 per Watt (in 1985 dollars) while increasing conversion efficiency and operating lifetimes (SERI, 1988).

Figure 5: Average Factory Prices for Photovoltaic Modules, 1975-1991



Source: Brown, et al., 1992, *Vital Signs*.

The Appendix, Part B represents the problem of allocating a solar R&D budget between research and promotional development. The mathematical result there shows that, in theory, the marginal dollar expended on research may now have greater economic value than a marginal dollar spent on development.

5. Conclusion

In the U.S., as with much of the industrialized world, photovoltaic and other renewable energy research lost much of its urgency through the 1980s and into the current decade as energy prices stabilized or declined. A young PV industry turned to developing countries for markets, often replacing the government's contribution to R&D funds with international development aid. 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 and too often leaving the distant consumer without the technical or financial ability to apply and sustain the technology. Industry representatives have justified market pushes as necessary to increase production and test technologies in the field (Caldwell, 1993).

The export market, and more specifically the developing country market, has absorbed much of international PV production. Between 1983 and 1991, the U.S. exported 41.8 MW and consumed 50.9 MW of PVs (EIA, 1992). Kyocera, a leading PV producer from Japan, exports over 90% of their PV modules (Maycock, 1993). 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.

Many in industry and government contend that PVs are economically competitive now, requiring little 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 in actual small-scale applications in developing countries and the U.S., we conclude that PVs are clearly not competitive now on economic grounds with remote fossil fuel options. We also note that factory prices have remained stable despite growing world production.

Still, funds currently spent on PV international aid may be many times greater than those spent on research. For instance, just one PV aid program--a $35 million dollar World Bank program in India (Asia Alternative Energy Unit, 1993)--exceeds the 1990 U.S. DOE appropriations for PV research of $34.3 million. Other U.S. aid sources include the United Nations as a user of U.S. funds, the U.S. Agency for International Development, the U.S. DOE, and countless non-governmental and philanthropic organizations which often serve as promoter, financial intermediary, exporter, importer, consultant, installer, and/or parts supplier.

Further distracting attention from needed research is the international response to the environmental threat of climate change. For instance, a $7 million Global Environmental Facility PV program in Zimbabwe is currently underway to offset growth in carbon dioxide (CO_2) emissions (GEF, 1992). The estimated cost of the program in terms of CO_2 offsets is $2,600 per metric ton of carbon. In contrast, other options are available to offset CO_2 at zero to negative net costs (see Rubin et al., 1992; and Drennen, Erickson, and Chapman, 1993).

Under the current U.S. administration, and in many other industrialized country governments, however, PV and other renewable energy research funding is on the rise. The 1994 U.S. DOE request for renewable energy research was

$327 million, 74% above 1993 allocations (Public Power Weekly, 1993). However, with their chronically low share of energy R&D allocation, renewables have lost a lot of ground. In 1989, the leading industrialized country governments spent just 7% of their $7.3 billion in energy research funds on all renewable energy technologies (Flavin and Lenssen, 1991). The U.S. General Accounting Office (1993) estimates that, 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 all renewable energy technologies combined (i.e. solar, wind, biofuel, and ocean).

In addition, more than a decade has been spent educating our future energy scientists in the areas of nuclear and conventional fossil fuel technologies. While these efforts have not gone in vain, the lack of university support for renewable energy education and research is apparent. In 1990, the DOE's Office of Energy Research allocated 0% of their basic renewable energy research funds to their University Research Support program. Universities received 14% of the Solar Energy Research Institute's subcontracts and educational support for 28 postgraduate researchers, 12 graduate students, and 31 undergraduate summer students (SERI, 1990).

In light of current economics, technology, and markets, the authors conclude that real-world policy makers need to place more emphasis on basic photovoltaic research and education. Solar electricity will be strongly needed in the future on environmental criteria, and further basic research as well as timely donor aid support will be required to bring it into the global market on a fully competitive, sustainable basis.

APPENDIX

PART A: Economic Value of Solar Costs, 80 Watt System Illustration

(1) $P = Z/Q,$

(2) $$Z = \frac{i(1+i)^n}{(1+i)^n - 1} K + A,$$

(3) $$Q = \frac{s * w * f}{1000 \frac{W}{kW}} * 365.25 \frac{d}{y}.$$

P = annual levelized cost in $/kWh, variable

Z = annual equivalent cost, $/y, variable

Q = annual usable output in kWh/y, variable

y = year

i = interest rate, 10%/y

n = operating lifetime, 10 years

K = initial investment in panels, invertor, controls, installation, $, e.g. $948 for 80 W system

A = amortized annual costs of battery replacement ($17.30/y) and repairs (7% of all preceding costs, or $12.01/y)

s = solar insolation index, 5.0, h/d

w = wattage rating of panels, 80 W

f = efficiency index, .728

Portable generator costs are calculated with an analogous method, but without battery and power conditioning costs, and including fuel costs and a higher repair percentage rate.

System Specifications

Photovoltaic System

i. PV module - installed at various Watt sizes ranging from 25 to 50. Larger systems use multiple modules.

ii. Battery - locally made 12V car batteries typically used. Capacities range from 60 to 100 amp-hours, e.g. a lawn tractor battery in the U.S.

iii. Charge control - three-diode state-of-charge indicator, system protection fuse, manual cut-off switch, and voltage converter for 9V radios. Panel acts as charger and one panel systems typically regulate their own charge.

iv. Installation - wiring, roof or stand mount, correct angling, battery and control area.

v. Efficiency Losses - panel loss through dirt, module inefficiency, and temperature induced voltage drop. Significant battery loss through charging.

vi. Repairs - blown fuses, broken switches, wiring, panel cleaning, and battery water filling and disposal.

vii. Consumption load - low wattage fluorescent and incandescent bulbs, 14W T.V.s and radios.

viii. Fuel and oil - none required for system operation.

Portable Generator

i. Generator - Honda offers 650W through 5000W portable sizes with associated differences in fuel efficiency, noise, AC/DC options, remote start, etc.

ii. Battery (optional) - most models can charge batteries for nighttime use while powering other items.

iii. Fuse box - fuse mounted on generator or install fuse and safety disconnect in house. A junction box is needed if more than one house is involved.

iv. Installation - wiring, storage area, fuel tank.

v. Efficiency losses - minimum; typically when overloaded.

vi. Repairs - cleaning, lubrication, spark plugs, fan belt.

vii. Consumption loads - lights, small refrig., water pump, entertainment, and quick consumptions (iron, blender, toaster, sewing).

viii. Fuel and oil - ex: 650W gen. consumes 0.13 gal./hr.; oil change every 2 weeks with heavy use.

PART B: Research or Development?

The problem is to maximize the net present value of solar energy use with respect to policy variables for development subsidies, and basic research expenditures. The current annual budget defines a constraint for combined solar development and research spending. The cost curve has positive private sector learning effect, public sector research effect, and current period scale economy. Excluded factors in this statement of the problem are (a) competitive goods such as conventional energy, (b) the non-market environmental losses or gains from conventional and solar energy use, and (c) the public policy variables related to conventional taxation. (The definitions follow Equation (10) in order of appearance.)

$$(1) \quad V_t = \int_0^{Q_t} P_t(Q_t)\,dQ - \int_0^{Q_t} C_t(Q_t, SUB_t, G_t, t)\,dQ - SUB_t - RE\$_t,$$

$$SUB + RE\$ = B, \quad SUB_t = SUB, \quad \text{and} \quad RE\$_t = RE\$;$$

$$G_t = \int_0^t RE\$_i\,di, \quad \text{or} \quad G_t = tRE\$.$$

$$(2) \quad V = \int_0^T \frac{V_t}{e^{rt}}\,dt.$$

(3) $P_t = \alpha_0 - \alpha_1 Q_t,$ $\qquad C_t = Q_t * \beta_0 Q_t^{\beta_1} SUB_t^{\beta_2} G_t^{\beta_3} t^{\beta_4}.$

$$(4a) \quad V = \int_0^T \frac{(\alpha_0 Q_t - \frac{\alpha_1}{2} Q_t^2)}{e^{rt}} dt - \int_0^T \frac{\beta_0 Q_t^{\beta_1+1} SUB_t^{\beta_2} (\int_0^t RE\$_i di)^{\beta_3} t^{\beta_4}}{e^{rt}} dt$$

$$- \int_0^T \frac{(SUB + RE\$)}{e^{rt}} dt - \lambda(B - SUB_t - RE\$_t), \quad or$$

$$(4b) \quad V = \int_0^T \int_0^{Q_t} \frac{P_t dQ}{e^{rt}} dt - \int_0^T \frac{Q_t * AC_t}{e^{rt}} dt - (SUB + RE\$) \int_0^T e^{-rt} dt - \lambda (B - SUB - RE\$).$$

$$(5) \quad \frac{\partial V}{\partial SUB} = \beta_2 \int_0^T \frac{\beta_0 Q_t^{\beta_1 + 1} \beta_2 SUB_t^{\beta_2 - 1} (\int_0^t RE\$_i di)^{\beta_3} t^{\beta_4}}{e^{rt}} dt - \frac{e^{rT} - 1}{r} + \lambda = 0.$$

$$(6) \quad \frac{\partial V}{\partial SUB} = \int_0^T \frac{\beta_2 C_t}{SUB e^{rt}} dt - \frac{e^{rT} - 1}{r} + \lambda = 0.$$

$$(7) \quad \frac{\partial V}{\partial RE\$} = \frac{\partial V}{\partial G} \frac{\partial G}{\partial RE\$} - \frac{e^{rT} - 1}{r} + \lambda = 0.$$

$$(8) \quad \frac{\partial V}{\partial RE\$} = \int_0^T \frac{t \beta_3 C_t}{RE\$ e^{rt}} dt - \frac{e^{rT} - 1}{r} + \lambda = 0.$$

$$(9) \quad \frac{\beta_2}{SUB} \int_0^T \frac{C_t}{e^{rt}} dt = \frac{\beta_3}{RE\$} \int_0^T \frac{tC_t}{e^{rt}} dt.$$

$$(10) \quad \frac{RE\$}{SUB} = \frac{\beta_3}{\beta_2} \frac{\int_0^T \frac{tC_t}{e^{rt}} dt}{\int_0^T \frac{C_t}{e^{rt}} dt}.$$

V_t = net social value in year t

P = price demand function for solar

Q = quantity solar used

C = total annual cost of solar to user

SUB = current annual development subsidy

G = cumulative investment in research

RE$ = current annual research expenditure

B = budget constraint for solar research and development

r = discount rate

V = present value of net social value

T = time horizon of analysis

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