RESIDENTIAL RURAL SOLAR ELECTRICITY IN DEVELOPING COUNTRIES

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Are photovoltaic (PV) systems appropriate for use in developing countries now? This paper presents an empirical review of the comparative costs of gasoline portable generators and PV systems and concludes that cost reduction is necessary before PV systems will be broadly competitive. Both private sector research and university research have important roles to play.

I. INTRODUCTION

This paper analyzes the current market conditions that influence the adoption and maintenance of solar electricity systems in developing countries. Renewable solar power may offer a different route to higher living standards for developing countries than does the path followed by industrialized countries. If so, then accelerating use of energy in developing countries need not be accompanied by accelerating releases of carbon dioxide, the major greenhouse gas. Similarly, solar energy would reduce growth in regional ozone, carbon monoxide, acid deposition, and particulates, as well as reducing reliance on imported oil.

The analysis here focuses on household PV (photovoltaic) systems for several reasons. Of course, other solar technologies are in use today, including household hot water systems and central station thermal systems (see Johansson et al., 1993, for a summary). In addition, one may broadly define solar energy as renewable energy, in the sense that biomass energy and hydro and wind power originate with solar-driven atmospheric forces. However, household PV electricity is a leading renewable technology both in research and application (Caldwell, 1994; Huacuz and Martinez, 1993; Hankins, 1993). Currently and in the past, PVs have claimed the largest share of U.S. federal appropriations for renewable energy activities (Golub and Brus, 1993). In the United States as well as in developing countries, PVs are beginning to penetrate markets accessible to PV's major competing technology, portable generators (Caldwell, 1994). U.S. capacity for remote household PV installations now is about 20 MW (megawatts), equal to approximately 7 percent of the small generator capacity (U.S. EPA, 1991; U.S. GAO, 1993). For a comparative perspective, consider that utility generating capacity in the U.S. is 700,000 MW (Electric Power Monthly, August 1993).

Caldwell (1994) defines several market segments and emphasizes solar competitive grid-connected electricity. In contrast, the analysis here examines rural markets not served by central grids.

ABBREVIATIONS

MMC: Marginal market cost
MNC: Marginal non-market cost
MSC: Marginal social cost
NGO: Non-government organization
PV: Photovoltaic
R&D: Research and development

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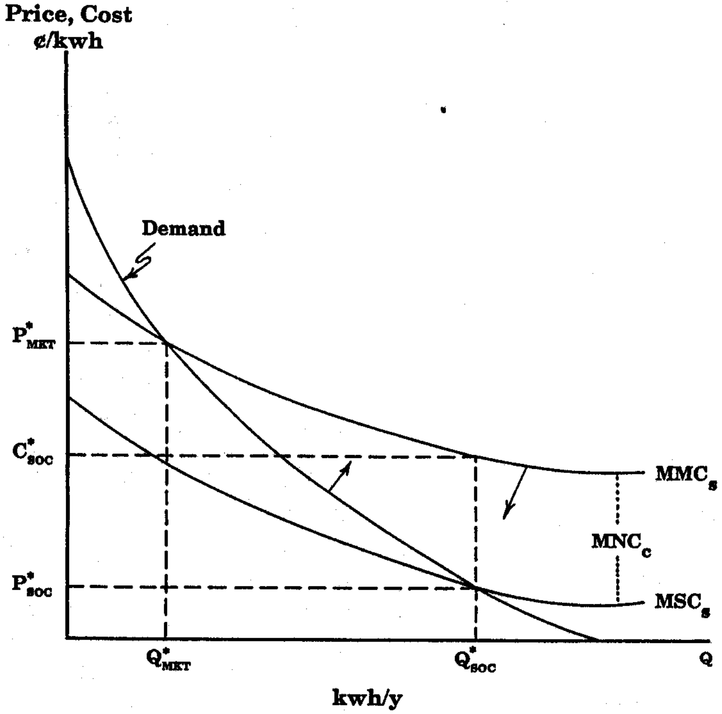
FIGURE 1
Solar Market and Social Equilibria



II. SCALE ECONOMY AND TECHNOLOGICAL INNOVATION

In terms of optimal public policy, economic logic implies that implementing solar PV technology should be promoted when the declining social cost of PV energy passes below the rising social cost of conventional energy generation. (Social cost here is the sum of market and externality costs.) Assuming that the externality cost of gasoline production and use is significantly greater than that for PV use, one should expect that private market outcomes would defer solar implementation to later periods than would be socially optimal.

With respect to producer costs for PV installation, analysts widely believe 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. Demand for solar 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 that shift the MMCs curve downward. These two factors are (i) the learning curve effect, over time, and (ii) the beneficial results of public investment in solar research.

Figure 1 represents the marginal social cost of solar (MSCs) 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 (P^*_{MKT}, Q^*_{MKT}) shows high price and cost and low sales for household PV. However, the social optimum is a much larger quantity, Q^*_{SOC}. In order to attain this social optimum quantity, government must subsidize the market price at P^*_{SOC}. The total financial subsidy in dollars is equal to the box with length Q^*_{SOC} and width $C^*_{SOC} - P^*_{SOC}$. Figure 1 shows that this amount is a substantial portion of the producer's total revenue.

The hypothesized joint existence of significant scale economies by producers and external social benefit from solar electricity use combine to offer strong economic incentive for developmental subsidy of PV use. Under these conditions, government support and donor aid clearly would promote economic efficiency. Figure 1 represents the economic logic of current solar development policy.

One alternative policy would be taxation of petroleum at a rate equal to its marginal non-market environmental cost. Economic efficiency would be promoted by correctly raising the user cost of gasoline generators relative to solar systems.

III. ECONOMIC ANALYSIS AND EXTERNAL COSTS

This 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.

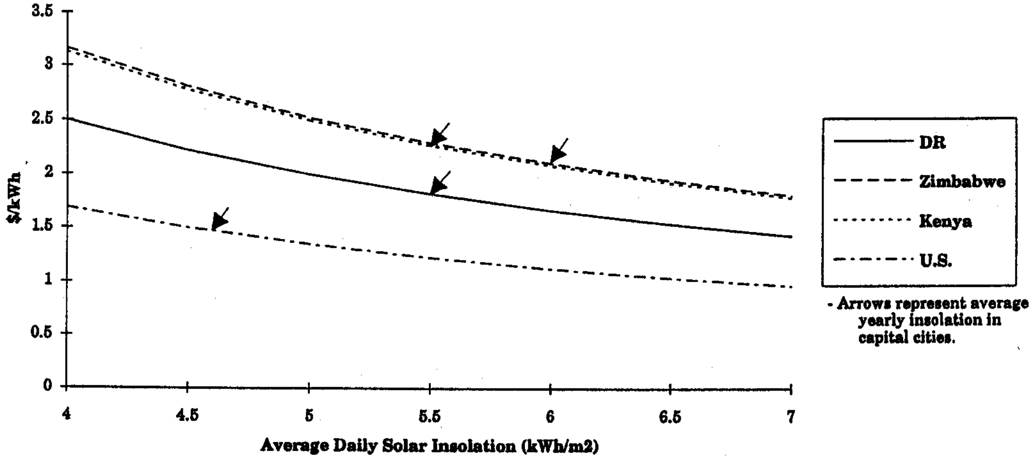
Caldwell (1994) notes that the portable diesel or gasoline generator is the most important competing technology to PV in rural markets. With smoothly functioning world markets, the pretax cost of electricity from portable generators would be fairly uniform throughout the world. Transportation of generators to and within developing countries would be similar everywhere: the transport cost of shipping a 500 Watt generator from Japan to New Mexico would be comparable to shipping a generator to the Dominican Republic or Africa. Similarly, the production cost of gasoline delivered to coastal areas should be nearly identical: a Shell refinery in Durban can use the same technology as a Shell Caribbean or Shell U.S. or European refinery, and the transport cost of crude oil to refineries is only a few pennies per gallon (Chapman, 1983, p. 126). The basic costs of installation for solar systems also should be similar throughout the world in locations near transportation systems.

In defining maximum energy production from a given site, a solar system is site-specific in that the incidence of solar insolation affects its electricity production. 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 percent between Ithaca and Arizona. Zimbabwe, other things being equal, would be 17 percent more costly than Arizona.

Usable solar electricity also is influenced by battery storage, AC-DC power conversion, and in general the capability of transferring electrical energy from the period of solar generation to periods of nighttime or cloudy day use.

As with portable generators, the unsubsidized, untaxed market cost of imported PV systems should be similar for developing country and U.S. locations with equivalent solar insolation. However, figure 2 indicates that actual cost curves are not similar. Figure 2 shows the full cost of a 48 Watt system in three developing countries and in the United States. (The Appendix, Part A summarizes the methodology.) The curves show that cost declines as insolation increases. The arrow shows aver-

FIGURE 2
Solar Insolation and Cost: Four Countries



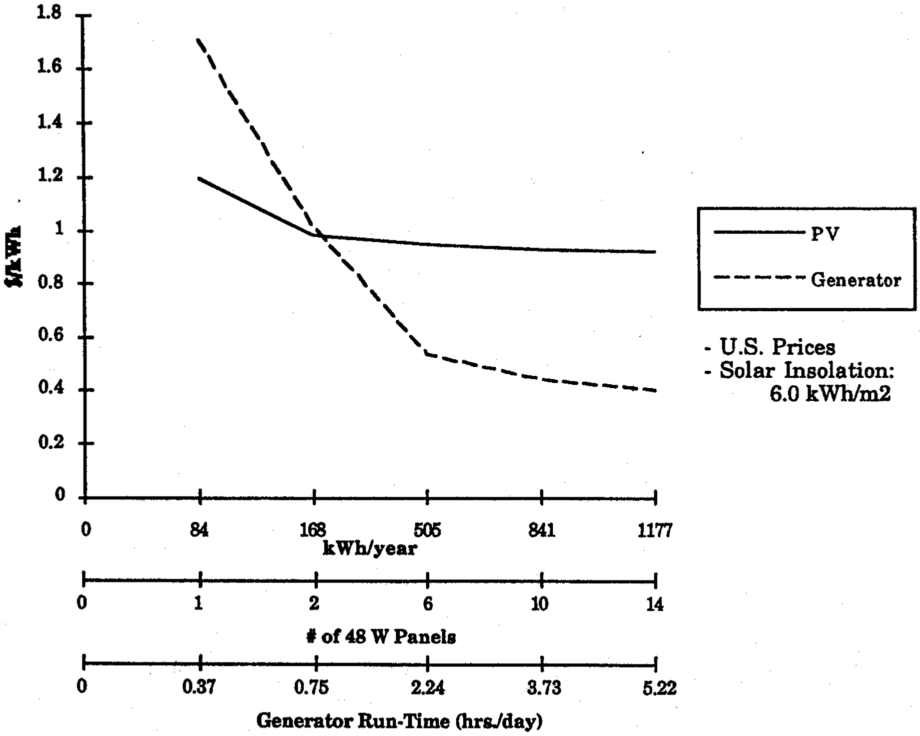
age annual insolation for each country. (Data for developing countries are from (Erickson and Chapman, 1993; Erickson, 1993; Hankins, 1993; Agras, 1994. U.S. data are from Schaffer, 1992; Erickson and Chapman, 1993.) For this modest capacity (48 Watts, 77 kWh/y in Zimbabwe), panel investment cost is 60 percent of annual levelized cost per kWh.

Figure 3 compares the cost per kWh of various sized PV systems with a 650 Watt portable generator. Portable generators now exhibit less cost per kWh than do PV systems for well-functioning markets. However, one should not assume that PV will never be chosen. Three factors favor PV systems. (i) A PV system is available at a lower capacity. At a modest cost for lights, radio, or television, a household can fully utilize the system. An under-utilized portable generator may have kWh costs comparable to those of the PV system (see the section of figure 3 to the left of 168 kWh/y). (ii) The absence of the noise and smell of generator operation also causes households to favor PV. Additionally, highly variable household monthly income may favor paying up front for months of solar power versus weekly gasoline expense. (iii) An inefficient parastatal petroleum company or an unreliable national government may lead a household to feel more secure with PV because the availability of gasoline may be unpredictable.

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 equally well. Field research suggests that components for both systems usually are available in countries with PV use (Agras, 1994; 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.

Table 1 shows current estimates of the environmental, health, and climate change external social cost of petroleum use in cents per kWh for output from a small generator. The authors listed studied sub-

FIGURE 3
Cost at Very Low Energy Levels



jects including tropospheric air pollution damage, national security costs, and greenhouse gas damage.

Note that Viscusi et al. (1994) analyze tropospheric air pollution, as does the first Hall column. Table 1 illustrates an upper bound in current quantified estimates of the external social cost of using gasoline in rural power generators. Therefore, the two Hall columns plus the Fankhauser entry, summing to 11.5¢ per kWh, represent "state-of-the-art" calculations now.

Figures 1, 2, and 3 show that external social cost pricing for gasoline would increase the range of electricity use where PV is preferred to a portable generator.

IV. GASOLINE PRICES, TAXATION, AND DONOR AID

The deflated retail price of gasoline has fallen 40 percent from 1988 (MER, 1994). However, projecting future prices with confidence is difficult. It does seem likely that the U.S. and other governments will continue to increase petroleum taxation. Figure 4 shows the interaction of gasoline prices and taxes with PV cost and donor aid.

The diamond curve reflects percentage increases in portable generating costs as a function of higher gasoline price or taxation. For example, increasing the U.S. cost of gasoline by 100 percent from $1 per gallon to $2 per gallon would raise the electricity cost from 30¢ per kWh to 55¢ per kWh. (As above, assume that U.S. cost curves before taxes reflect the lower bound of international cost curves for gasoline and PV generation.)

Figure 4 also shows the impact of donor aid on PV cost. The "X" at $1.12/kWh on the vertical axis represents no donor aid, at an interest rate of 10 percent. If a donor

TABLE 1

External Social Cost (ESC) Estimates of Petroleum Use in Small Generators

Author	Hall	Hall	Viscusi	Fankhauser
Type of externality	ozone and particulate damage	national security	gasoline air pollution	greenhouse gas
ESC as reported	\$11.59 per bl	\$10.04 per bl	15¢ per gal	\$20.30 per tonne carbon
ESC per kWh gasoline generator	5.5¢/kWh	4.8¢/kWh	3.0¢/kWh	1.2¢/kWh

Sources: See references. Tonne is metric ton. Hall sources are 1992A, B. Viscusi estimate is higher for diesel oil; Viscusi figure overlaps with Hall ozone and particulate figure. There are no published estimates on generator noise and odor external cost. Generation requires 0.2 gallons gasoline per kWh generated. Gasoline refining and marketing costs are 40¢–50¢ per gallon (Chapman, 1983).

provides an interest-free loan, the subsidized cost to the user moves down to 70¢ per kWh, at the dark box on the vertical axis. The declining box curve represents declining, subsidized cost to the user as a donor agency provides an increasing percent of initial cost in addition to a no-interest loan on the proportion of cost assumed by the user. Note that a combination of an interest-free solar loan and 50 percent donor aid coupled with a 50 percent 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, PV fabrication is supported by a network of international donors supplying materials, technical assistance, large scale promotion, and low interest loans. The donor aid probably is some multiple of the cost 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 is influenced heavily by the dedicated commitment of a U.S. NGO run by an expatriate with a high level of technical and marketing skills. International aid supports this NGO.

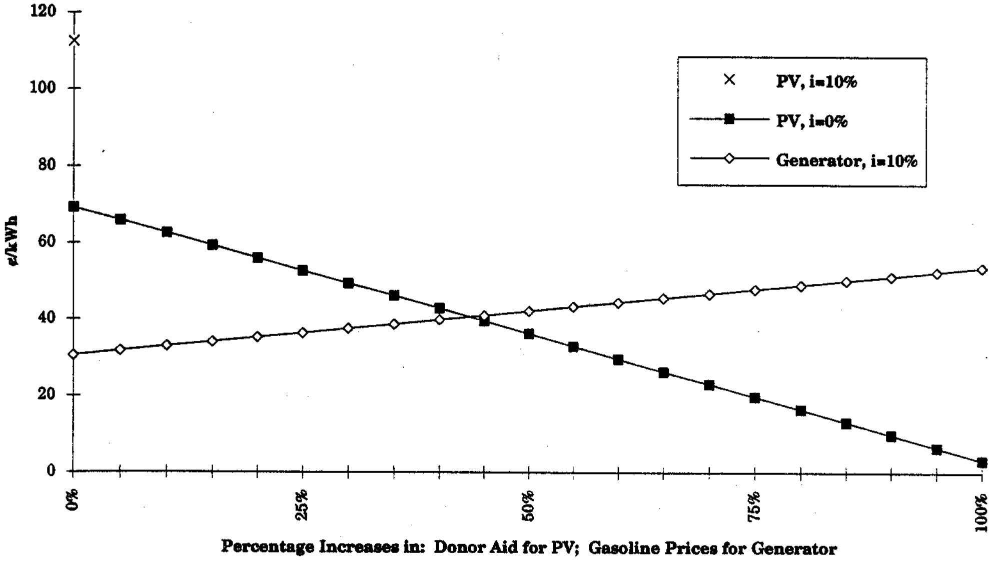
Given the apparent importance in the near term of donor aid support for developing country applications, the question arises as to the best allocation of solar research and development (R&D) Is the return greater for a dollar invested in a university laboratory on basic research or for a dollar invested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

Figure 5 represents the decline in PV costs over time, primarily demonstrating the learning curve effect. Figure 5 shows falling cost per kWh, but the rate of reduction is declining. This reduction in market cost reflects 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).

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

FIGURE 4

Cost with Gasoline Price, Tax Increases, and PV Donor Aid
U.S. Prices ¢/kWh



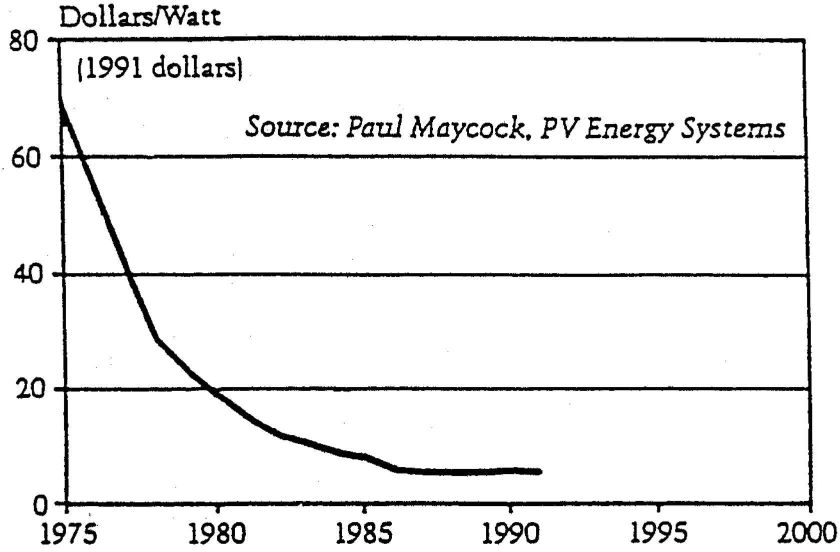
Note: Donor aid represented as percent of initial solar cost. Future gasoline price or tax increase represented as percent of current cost.

V. CONCLUSION

In the United States as in much of the industrialized world, PV and other renewable energy research lost much of its urgency through the 1980s and into the current decade as real 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) describe the new attention to renewable energy technology transfer as a "supply push rather than a demand pull" that significantly subsidizes the solar industry and too often leaves the distant consumer without the technical or financial ability to apply and sustain the technology. Industry representatives have justified market pushes as necessary in order 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 United States exported 41.8 MW and utilized 50.9 MW of PVs (U.S. EIA, 1992). Kyocera, a leading PV producer from Japan, exports over 90 percent 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 industry and government observers contend that PVs are economically competitive now and require 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 United States reveals that on economic grounds PVs clearly are not competitive now with re-

FIGURE 5
Average Factory Prices for Photovoltaic Modules
1975–1991



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

mote fossil fuel options. Additionally, factory prices have remained stable despite growing world production.

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. Another World Bank program is investing $7 million in PV installations in Zimbabwe (GEF, 1992; Agras, 1994). 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 non-governmental and philanthropic organizations that often serve as promoter, financial intermediary, exporter, importer, consultant, installer, and/or parts supplier.

PV and other renewable energy research funding currently is increasing. One result is the plan by Canon, Inc. to build a U.S. factory using new silicon technology. This project developed from basic research in the private and public sectors (Bishop, 1994).

Chapman and Drennen (1990) express concern that developing countries need to increase their incomes and energy use. Drennen et al. (1993) investigate solar electricity's potential role in deferring greenhouse gas emissions in developing countries. The analysis here concludes that non-grid rural electricity from photovoltaic systems is not now economically viable on a broad scale.

In light of current economics, technology, and markets, real-world policymakers need to place more emphasis on basic photovoltaic research and education. Environmental criteria dictate that countries will need solar electricity in the future. Thus, further basic research in both the private and public sectors are required to bring solar electricity into the global market on a fully competitive, sustainable basis.

APPENDIX

PART A: Economic Value of Solar Costs, Illustration with 48 Watt System in the Dominican Republic

$$P = Z / Q, \tag{1}$$

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

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

P = annual levelized cost in \$/kWh, variable, e.g. \$1.82/kWh

Z = annual equivalent cost, \$/y, variable, e.g. \$140.27/kWh

Q = annual usable output in kWh/y, variable, e.g. 77.1 kWh/y

y = year

i = interest rate, 10 percent/y

n = operating lifetime, 10 years

K = initial investment in panels, invertor, controls, installation, \$, e.g. \$550 for 48 W system

A = amortized annual costs of battery replacement (\$44.04/y) and repairs (5 percent of all preceding costs, or \$6.68/y); total \$50.72/y

s = solar insolation index, 5.5, h/d

w = wattage rating of panels, 48 W

f = efficiency index, .8

Calculating portable generator costs involves using an analogous method while excluding battery and power conditioning costs and including fuel costs and a higher repair percentage rate. Erickson and Chapman (1993) describe the parametric assumptions (see also Hankins, 1993; Schaffer, 1992).

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 United States.

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 5,000W 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 occur when overloaded.

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

vii. Consumption load—lights, small refrigerator, water pump, entertainment, and quick consumptions (iron, blender, toaster, sewing).

viii. Fuel and oil—e.g., 650W unit consumes 0.13 gal./hr.; oil change every two 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 (i) competitive goods such as conventional energy, (ii) the non-market environmental losses or gains from conventional and solar energy use, and (iii) the public policy variables related to conventional taxation. The definitions follow equation (10) in order of appearance.

(1)
$$V_t = \int_0^{Q_t} P_t(Q_t)dQ$$

$$- \int_0^{Q_t} C_t(Q_t, SUB_t, G_t, t)dQ - SUB_t - RE\$_t,$$

$$SUB + RE\$ = B, \quad SUB_t = SUB,$$

$$\text{and } RE\$_t = RE\$;$$

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

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

(3)
$$P_t = \alpha_0 - \alpha_1 Q_t,$$

$$C_t = Q_t * \beta_0 Q_t^{\beta_1} SUB_t^{\beta_2} G_t^{\beta_3} t^{\beta_4}.$$

(4a)
$$V = \int_0^T \frac{(\alpha_0 Q_t - \frac{\alpha_1}{2} Q_t^2)}{e^{rt}} dt$$

$$- \int_0^T \frac{\beta_0 Q_t^{\beta_1+1} SUB_t^{\beta_2} (\int_0^t RE\$_i di)^{\beta_3} t^{\beta_4}}{e^{rt}} dt$$

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

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

$$-(SUB + RE\$) \int_0^T e^{-rt} dt - \lambda(B - SUB - RE\$).$$

(5)
$$\frac{\partial V}{\partial SUB} = \beta_2 \times$$

$$\int_0^T \frac{\beta_0 Q_t^{\beta_1+1} \beta_2 SUB_t^{\beta_2-1} (\int_0^t RE\$_i di)^{\beta_3} t^{\beta_4}}{e^{rt}} dt$$

$$dt - \frac{e^{rT} - 1}{r} + \lambda = 0.$$

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

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

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

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

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

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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