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Solar Energy for Village Development

Norman L. Brown and James W. Howe

Most of the people in the developing countries of Asia, Africa, and Latin America live in rural areas. Progress in these areas depends on finding substitutes for human muscle energy, which is now relied on for many village tasks.

Summary. The National Academy of Sciences held a joint workshop with the Government of Tanzania last August on the potential of solar energy for the villages of that country. Costs of five solar technologies (mini–hydroelectric generators, wind, methane generation from organic wastes, photovoltaic cells, and flat-plate solar collectors) were compared with costs of diesel-generated electricity and with electricity from the national grid. Each of the five technologies is either now competitive with diesel or will be in a few years. Although the figures presented are not conclusive since they are derived from calculations rather than an actual test, the results are encouraging enough to warrant serious testing in Third World villages.

The prohibitive costs of large central generators and massive transmission and distribution systems, as well as the slow pace of the spread of rural electrification programs, discourage hopes that rural energy needs can be met with a national electric grid. Hence, we have inquired into the potential of small-scale technologies that use renewable energy sources coming from the sun. Current solar energy comes from four major systems: (i) photosynthesis, which is the basis of all life, both plant and animal; (ii) the water cycle, which is driven by the sun; (iii) wind, caused by the atmospheric pressure differences due to changing amounts of solar energy falling on different places; and (iv) direct sunshine. Proven small-scale technologies exist for using each of these solar energy systems.

In photosynthesis, biogas plants use anaerobic bacteria to turn animal, human, and crop wastes into methane gas and, at the same time, leave a residual slurry that is useful for fertilizer. It has been reported that there were 1.2 million biogas plants installed in China in the first 6 months of 1976 alone, and that 4.7 million are now in operation (*1*). The technology appears to be proving itself and is improving all the time. Methane can be used for cooking, crop drying, power generation, and various other purposes.

To make use of the water cycle, a number of very small hydroelectric generators are now being manufactured for as little as $800. Miniature units producing only a few hundred watts or a few kilowatts can operate either with a small dam or simply by the flow of a small stream. In China, it is reported, there are 60,000 such units averaging about 40 kilowatts in capacity that successfully supply most of the electricity used by three-quarters of China's rural communes (*1*, pp. 27 and 28). In the 19th and early 20th centuries, most of New England's commercial power came from small hydrofacilities.

Windmills had long since proved themselves in Holland and the plains of the United States before they were driven out of existence by rural electrification—originally based on coal and later on cheap oil.

At least two small-scale technologies are available to make use of the direct rays of the sun. One is a flat-plate collector for space and water heating but which could also serve for activities such as crop and fish drying, distilling water, and refrigerating. The other technology for collecting the direct rays of the sun to generate electricity is a solar cell or photovoltaic array such as that used to power spacecraft.

Such promising technologies could be useful for a variety of tasks in rural areas. This potential is described in Table 1, where 14 technologies are applied to 15 common village tasks with the result that there are 44 applications that seem useful and 28 applications that seem marginally useful.

But what of costs? Are these not all technologies that require years more of research or the establishment of mass markets to become cost competitive with conventional energy sources? So few good data have been kept on the costs and performance of such technologies in actual village situations that we cannot answer this question completely. However, some preliminary calculations suggest that at least five technologies now "on the shelf" are, or soon will be, cost effective when compared with either diesel electric generation or the existing electric grid in the case of Tanzanian vil-

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lages. These calculations were made in Tanzania during a 10-day workshop jointly sponsored by the U.S. National Academy of Sciences and the Tanzanian National Scientific Research Council. For a week, this workshop group (*2*) poured over calculations of the costs of performing certain village tasks (i) with diesel motors, (ii) with electricity from the Tanzanian electric grid, and (iii) with five small-scale renewable technologies. The results surprised even the experts. Each of these five technologies appeared to be now or soon competitive with diesel. A number of them compete well with the electric grid for certain village tasks. These results are valid despite the assumption that capital to build the facility costs 10 percent and must be repaid during the life of the equipment. In actual fact, a great deal of capital is often available to developing countries on far more generous terms. This is more advantageous to solar energy over the life of the project than to diesel power because capital costs of the former are high relative to operating costs while the reverse tends to be more true of diesel power. Thus, for example, it may be possible to borrow nearly 100 percent of the total life of project costs for a photovoltaic installation (since such costs consist nearly entirely of initial capital), whereas for the initial capital for diesel one could borrow only about one-eighth of the life of project costs. Hence cheap capital favors solar over diesel energy.

Of course the panelists recognized that a final determination of whether a given technology should be applied to a given village situation depends not only on the financial costs, but also on availability of resources, social obstacles, social benefits, institutional barriers, long-range power requirements, and long-range development goals. In the short time available to them, they focused on estimating financial costs of the technologies considered most likely to be applicable with the understanding that this was but a first step in the decision-making process (*3*).

Basis for Cost Comparison

A hypothetical village of 300 families was chosen as a basis for estimating the magnitude of financial investment needed. It was assumed, for these initial installations, that the needs of each family could be met, on the average, by the use of 1 kilowatt-hour per day (300 kWh total) to be applied to lighting, operation of a village television receiver, radio communications, pumping water, or grinding grain. At this rate of energy consumption, Tanzanians receiving central-station generated electricity from TANESCO (Tanzania Electric Supply Company) would pay, on the average, about 0.93 shilling (*s*) per kilowatt-hour (*4*) (the U.S. equivalent is \$0.113/kWh). It was assumed further that the 300 kWh/day could be supplied either on a 5-hour basis, that is, at the rate of 60 kW, or for 20 hours, that is, at a rate of 15 kW.

Technologies of Energy Supply

Five technologies were chosen as illustrative examples, on the basis of their immediate or short-term availability (or both) (*5*).

Photovoltaic power generators. The analysis of the cost of supplying electrical power by a solar-cell array was based on a cost estimate of \$20 (U.S.) per watt-peak (W_p). Although, in a recent large-scale purchase by the U.S. government, the cost was \$15/W_p, a cost of \$20/W_p was used in these estimates on the assumption that the more favorable price would not be available for an initial small-scale purchase.

Cost calculations are summarized in Table 2 (*6*). The size of the array needed to supply 300 kWh daily was based on World Meteorological Organization insolation data for Tanzania (*7*). These figures indicate that an array with a peak power capacity of 1 kW will produce, on the average, 5.3 kWh daily. Thus, for 300 kWh/day, a generous estimate of 60 kW_p was used. An interest rate of 10 percent per annum, the prevailing rate in Tanzania, was used to calculate financing costs. The estimated cost of energy provided by photovoltaics, 11*s*/kWh, is approximately 12 times the average current cost of electricity in Dar es Salaam, as noted above.

In view of the predicted drop in the cost of photovoltaic devices—the Department of Energy looks to a cost of \$0.50/W_p by 1985, or earlier—it is interesting to see how sensitive the electricity cost is to the array cost. For an array cost of 4.1*s*/W_p (\$0.50/W_p) the total system cost for this example would be 528,000*s* with the same battery costs assumed. The annual cost would then be 94,000*s*, and the cost of electricity 0.83*s*/kWh, or 10 percent less than the current cost of electricity from the grid. The "break-even" array cost, that is, the cost of photovoltaics that would enable electricity to be generated at the average current selling price in Dar es Salaam, would be 5.28*s*/W_p or \$0.64/W_p. Thus, the use of photovoltaic devices to generate electricity for the villages of Tanzania is likely to be economically competitive within 10 years (*8*). Moreover, for any village that wants small amounts of electricity now but is not within reach of the grid (discussed later) photovoltaic devices may already be cost effective compared with conventional alternatives.

Small-scale hydropower. In the mountainous regions of Tanzania there are many small streams and rivers with a flow of water sufficient in quantity and reliability to be considered as a source of small-scale hydroelectricity. This technology is a mature one, with devices of a variety of sizes available "off the shelf" not only in the United States, but in many other countries (*9*). With known cost figures as a basis, four cases were considered, as shown in Table 3. These four cases provide for two basic situations—one in which the needs of the village (300 kWh/day) would be supplied directly by the generator during the hours of use (that is, 60 kW), and one in which a smaller generating capacity (that is, 15 kW) would be used with storage batteries to supply the required 300 kWh/day over a period of 20 hours.

The cost calculations for these four ways of supplying hydroelectric power are summarized in Tables 4 to 6. For the purposes of this exercise, it was assumed that dams and penstocks, if needed, could be constructed with local labor and materials (timber and earth) at no significant capital costs (*10*). The water requirement estimates were based on data supplied by manufacturers of turbine or generator (or both) systems of the scale discussed. In all cases, where battery storage was required, it was assumed that the cost of the batteries would be amortized over the 6-year life expected for that subsystem, in order to allow for its replacement as needed, independent of the lifetime or amortization rates (or both) for the other equipment. As with the dams and penstocks, no cost figures were included for protective housing for batteries or power-conditioning equipment, on the assumption that locally available materials would suffice. (For all of these cases, some maintenance would be advisable. At an estimated cost of 1000*s*/month, this would add 0.10*s*/kWh to each of the cost figures.) Any of these assumptions might not be valid in specific circumstances; nevertheless the estimates show that small-scale hydroelectric installations are cost competitive with present large-scale systems—to say

Table 1. Solar energy applicability matrix. Animals are included as a solar technology (based on photosynthesis). For many villages the use of animals would represent a modernizing step. It includes the use of dung for burning or fertilizing. Source: adapted from a presentation by J. R. Williams at the Tanzanian workshop. Symbols: ++, applicable; +, somewhat applicable; −, not applicable.

Solar technology	Energy use													
	Water pumping	Lighting	Cooling	Communications	Water desalting	Spinning	Sawing	Heating: Cooking	Heating: Space	Heating: Domestic water	Grinding	Drying	Transport	Fertilizer
Solar cells (flat plate)	++	+	+	++	−	+	−	−	−	−	++	−	−	−
Flat-plate collectors	++	−	++	−	−	−	−	−	++	++	−	++	−	−
Concentrating collectors	++	+	++	++	+	+	+	++	+	−	++	−	−	−
Solar, stirling	++	+	+	−	−	+	+	−	−	−	+	−	−	−
Solar, rankine	++	+	+	−	−	+	+	−	−	−	+	−	−	−
Wind (mechanical)	++	−	−	−	−	+	+	−	−	−	++	−	−	−
Wind generator	++	++	+	++	−	+	+	−	−	−	++	−	−	−
Water (mechanical)	++	−	−	−	−	++	++	−	−	−	++	−	−	−
Hydroelectric	++	++	++	++	−	++	++	−	−	−	++	−	−	−
Bioconversion wood/pyrolysis	−	+	−	−	+	−	−	++	++	++	−	++	−	+
Biogas	++	++	+	−	−	−	−	++	−	+	−	+	+	++
Solar cooling equipment	−	−	++	−	−	−	−	−	−	−	−	−	−	−
Draft animals	++	−	−	−	−	−	−	+	−	+	++	−	++	++

nothing of the serious environmental and social consequences of large-scale hydroelectric projects—and are worth serious consideration in rural areas.

As a result, the panelists felt that it would be useful to extrapolate these estimates to the case where a large region of, say, 500 villages would be supplied with perhaps as many as 500 small hydroelectric generating units—assuming, of course, that sufficient rainfall and water flow rates were available. As an example, the total capital requirement for case 1 would be 330 million shillings. If a loan from the International Development Association (IDA) (the "soft-loan window" of the World Bank) were available, the economics of small-scale hydroelectricity applied on a large scale are very attractive.

For such a loan, no payment is required for the first 10 years; the loan is repayable, in equal annual installments over the next 40 years, at an annual interest rate of 0.75 percent. For this example, this would mean a financing cost of 9.6 million shillings per year from years 11 through 50. If the energy generated were sold to the villagers at the cost figures calculated in Table 6, the annual income would be 53 million shillings if the loan were a conventional 10-year loan, and 35 million shillings if it were a conventional 30-year loan. This would provide the government with between 25 and 40 million shillings for other projects. On the other hand, if energy were sold at a rate just sufficient to meet the 40-year cost of the IDA loan, the rate would be 0.17*s*/kWh, a figure less than one-fifth the current price of electricity in Dar es Salaam, and a cost well supportable by the villages electrified in this scheme. (This is approximately 1*s* per week.)

The four hydroelectric cases considered were based on a use, by the villagers, of 200 watts of electricity for 5 hours per day. For cases 3 and 4, this is the total capacity of the system. For cases 1 and 2, however, the system would be capable of supplying energy at the same rate (60 kW) day and night for 24 hours. If this capacity were used for more than 5 hours daily, the cost per kilowatt-hour could be reduced by as much as a factor of 4 or 5. That is, with load factors greater than 0.2 (5 hours' use per day), the cost of electricity production by small-scale hydropower systems of the type considered could approach 0.1 to 0.2*s*/kWh.

Biogas generation. The generation of methane from human, animal, and agricultural wastes is a process that is finding more and more use in developing countries, as people grow more aware of the potential of these "waste" materials as a source of both energy and fertilizer

Table 2. Cost of supplying electricity by means of photovoltaic generators. Financing costs were based on amortization of the loan in equal yearly installments.

Base data	
Lifetime of silicon solar cells	20 years
Lifetime of batteries	6 years
Efficiency of batteries	85 percent
Cost of silicon solar cells	160*s*/W_p
Cost of batteries	800*s*/kWh
Equipment costs	
Solar-cell array, 60 kW_p at 160*s*/W_p	9,600,000*s*
Battery storage	
(300 kWh at 85 percent efficiency)	
353 kWh at 800*s*/kWh	280,000*s*
Total equipment costs (approximate)	10,000,000*s*
Financing costs	
Solar-cell array	
9,600,000*s* at 10 percent for 20 years	1,100,000*s*/year
Batteries	
280,000*s* at 10 percent for 6 years	64,000*s*/year
Total cost of financing (approximate)	1,200,000*s*/year
Cost of electricity	
Total energy generated	110,000 kWh/year
Unit cost	11*s*/kWh

Table 3. Types of hydroelectric power equipment considered.

Case	Power			Storage required	Generating capacity (kW)
	Type generated	Type used	Conditioning required		
1	d-c	a-c	Yes	No	60
2	a-c	a-c	No	No	60
3	d-c	a-c	Yes	Yes	15
4	a-c	d-c	No	Yes	15

Table 4. Water requirements for supplying hydroelectricity by small-scale systems.

Power (kW)	Head (m)	Flow (m^3/min)
	48	12
60	24	25
	12	50
	6	100
	24	6
15	12	12
	6	24

Table 5. Base data for cost of supplying hydroelectricity by means of small-scale systems.

Item	Lifetime (years)	Unit cost (*s*)
Generator/turbine	30	4000/kW
Power conditioning	30	6/W
Batteries (85 percent efficiency)	6	800/kWh

Table 6. Cost of small-scale hydroelectric systems (in shillings). The cost of dams and penstocks was not included.

Item	Case 1	Case 2	Case 3	Case 4
Cost of equipment				
Generator/turbine	240,000	240,000	60,000	60,000
Power conditioning	360,000	0	90,000	0
Installation	60,000	24,000	15,000	6,000
Subtotal*	660,000	265,000	165,000	66,000
Battery storage	0	0	280,000	280,000
Installation	0	0	28,000	28,000
Subtotal	0	0	308,000	308,000
Total (approximate)	660,000	270,000	470,000	370,000
*Financing costs at 10 percent annual interest rate**				
Annual cost in shillings†				
30-year loan	70,000	29,000	89,000	78,000
10-year loan	107,000	44,000	99,000	82,000
Cost of electricity (*s*/kWh)‡				
30-year loan	0.64	0.26	0.81	0.71
10-year loan	0.97	0.40	0.90	0.75

*Based on amortization of the loan in equal yearly installments. †In both cases, it was assumed that the cost of the battery storage would be amortized over 6 years. ‡Based on 110,000 kWh/year.

Table 7. Cost of supplying cooking fuel, lighting, mechanical power, and electricity by biogas.

Base data	
Cattle dung	10 kg/day per cow
Biogas production (at 0.06 m^3 per kilogram of dung)	0.6 m^3/day per cow
Energy content of biogas as 60 percent methane*	11 kWh/m^3
System lifetime	20 years
Conversion efficiencies	
Internal-combustion engine	25 percent
Electrical generator	80 percent
Plant cost	
Single-family plant (3 m^3)	6000*s*
Financing costs†	
Single-family plant, 6000*s* at 10 percent for 20 years	705*s*/year
Engine/generator to provide 1 kWh/day, 5400*s*‡ at 10 percent (5 hour/day)	5940*s*/year
Engine to provide 1 kWh/day, mechanical energy, 3200*s*‡ at 10 percent (4 hour/day)	3520*s*/year
Energy costs§	
Cooking and lighting directly by gas (20 kWh/day)	0.10*s*/kWh
Cooking and generation of electricity at 1 kWh/day	18.2*s*/kWh
Cooking and generation of mechanical power at 1 kWh/day	11.6*s*/kWh

*This means that 4 kWh of biogas energy is available daily from each cow. †Based on amortization of loan in equal yearly installments. ‡Retail costs, Dar es Salaam, August 1977. §Cost of energy production only—does not include cost of appliances or cost of collecting dung.

(*11*). Indeed, several biogas plants are operating in Tanzania, and a body of experience in their construction and operation is being accumulated (*12*). Thus, it was natural for the workshop participants to consider the use of biogas not only for village lighting and cooking, but for the generation of electricity or mechanical power. For this exercise, the use of cattle dung was assumed, with average production rates and methane concentrations. Furthermore, lighting both by a gas-mantle lantern and with generated electricity was considered. The calculations are outlined in Table 7.

Analysis of the data shows that gas requirements for cooking three times a day are approximately 1.4 m^3/day per family, which could be supplied by dung from three to four cows. In contrast, to supply the electric lighting needs of a family (1 kWh/day) by using the biogas to operate an engine-generator set would require heat energy of 5 kWh/day, which could almost be supplied by one cow. This method of lighting, therefore, is almost four times as efficient, in energy use, as a gas-mantle lantern, albeit it requires a much greater capital investment. Finally, this same amount of gas—the gas supplied by one cow—would provide mechanical power alone at 1 kWh/day.

Another potential use for biogas, as a replacement for wood and charcoal, is in firing clay pottery used for water and cooking vessels. For small-scale production, estimates based on gas-fired firebrick kilns indicate that about 8 m^3 of methane, over a period of about 5 hours, would be required to fire earthenware at 1000°C in a kiln having a volume of about 0.2 m^3 (6 cubic feet). This is the equivalent of about 13 m^3 of biogas, which could be supplied by a 4-day accumulation from the dung of five cows. Larger production capacities—for instance, for a village industry—could be available by scaling-up the above estimate accordingly, and would represent another potential use for community digesters.

To summarize then: (i) heat energy, even from a single-family biogas plant, can be supplied at well below (less than one-ninth) the equivalent energy cost of electricity, and (ii) Ujamaa villages lend themselves readily to communal systems. Because of the economies of scale in biogas plant construction such communal systems (for example, schools, community latrines, community cattle-dung digesters in Masai villages) should be seriously considered.

Windmill generators. The use of windmill generators to supply a village's proposed electrical energy needs was considered in this exercise. However, even though the financial costs can be reasonably well estimated, measurements of wind-velocity and duration must be made to determine the suitability of any proposed site before any plans for a windmill project are contemplated.

The estimates that were made (Table 8) assume minimum wind speeds of about 12 miles per hour (5 m/sec) for an average of about 10 hours daily throughout the year. With windmill generators of a size reasonably available (10 kW), this would provide an average of 100 kWh daily, with electricity costs of less than 2*s*/kWh. This means, also, that to provide the proposed 300 kWh daily to a village of 300 families, three such installations would be required. If the task to be performed is pumping water, serviceable wind pumpers can be made with substantial savings by using local materials and skills. Thus, for example, in the Omo River Valley in Ethiopia, simple sail wind pumpers were built with Ethiopian materials following a design long used in Crete. The costs of mills that pumped 800 imperial gallons of water per hour, an elevation of 9 feet in winds of 13 miles per hour, was only $375 for each sail mill (*13*).

Solar refrigeration. Having visited a village where fishing was one of the major activities, the workshop panelists considered the possibility of using solar cooling to enable the villagers to preserve their fishing catch long enough to market the excess over their local needs. The cost of cooling and preserving a catch of 500 kilograms—typical for a day's fishing at the village visited—was calculated, on the basis of the use of local materials and labor for the container and its insulation, and commercially available collector. Estimates were based on the assumption that ammonia-based cooling systems could be used since the units will be located out of doors, and that they could be constructed in Tanzania. The container was assumed to be a 1-m cube, the cost of the chiller unit was estimated from known costs of available machines, and current U.S. costs of collectors were used. The results, based on the assumptions stated, are shown in Table 9. They indicate that solar refrigeration would cost only slightly more than the current cost of electricity alone, assuming a 5-year equipment life.

Conventional Technologies

The preceding analyses, as was noted earlier, compared the cost of generating electricity to the current selling price from the grid. To provide a useful context for this comparison, the costs of supplying electricity by extension of the present grid, and by local diesel generators, were examined.

Distribution grid to a village. This situation is based on either eventual extension of transmission lines to cover the country to the extent of coming within 20 km of every village, or constructing distribution systems to villages within 20 km of present transmission lines. In view of the overwhelming cost of the first alternative, serious thought was given only to the second. On this basis, it was assumed that a village of 300 families would occupy about 16 km^2 at a distance of some 20 km from a 33-kV transmission line. A summary of the analysis is given in Table 10. Transmission line costs (33 to 11 kV with a transformer of 500 kW) and substation (11 kV to 400 V at 5 kW) costs and connection costs came to an estimated total of about 2.18 million shillings. Financing costs, based on a 20-year life for the system, and a 10 percent annual rate of interest, would be about 256,000*s* per year. If this system were fully utilized (that is, load factor of 1.0) the unit cost would be 0.06*s*/kWh. Usually a grid system is poorly matched to village needs, however. In the case

Table 8. Cost of supplying electricity by means of windmill generators.

Base data	
Useful life of windmill generator	15 years
Lifetime of batteries	6 years
Efficiency of batteries	85 percent
Equipment costs	
Windmill generator (10 kW)	170,000*s*
Wiring, controls	42,000*s*
Installation	42,000*s*
Battery storage—(100 kWh at 85 percent efficiency) 118 kWh at 800*s*/kWh	94,000*s*
Total equipment costs (approximate)	350,000*s*
*Financing costs**	
Windmill generator, wiring, installation, 254,000*s* at 10 percent for 15 years	33,000*s*/year
Batteries, 94,000*s* at 10 percent for 6 years	22,000*s*/year
Total cost of financing (approximate)	55,000*s*/year
Cost of electricity	
Total energy generated	36,000 kWh
Unit cost	1.5*s*/kWh

*Based on amortization of loan in equal yearly installments.

Table 9. Cost of solar refrigeration of fish.

Base data	
Lifetime of equipment	5 years
Weight of fish (M) chilled daily	500 kg
Specific heat of fish (C_p) (estimate)	1 cal/g·°C
Storage time (t)	24 hours
Ambient temperature	25°C
Cold storage temperature	5°C
Surface area (A) of insulated box	6 m^2
Thermal conductivity (K) of walls*	10^{-4}cal/sec·cm·°C
Wall thickness (d)	10 cm
Hours of sunshine (average)	6
Heat requirements	
Cooling (Q_c)	
$Q_c = M{\cdot}C_p{\cdot}\Delta T$ = 10,000 kcal/day	
Losses (Q_L)	
$Q_L = K{\cdot}A{\cdot}\Delta T{\cdot}t/d$ = 1,000 kcal/day	
Total heat requirement	11,000 kcal/day
Equipment costs	
Chiller (⅔ ton = 2,000 kcal/hr)	(estimated) 8,000*s*
Collector (10 m^2)	(estimated) 11,200*s*
Total equipment cost	(approximated) 19,000*s*
Financing cost†	
19,000*s* at 10 percent for 5 years	5,000*s*/year
Cooling cost	
Energy required for cooling	5,100 kWh/year
Unit cost	0.98*s*/kWh

*Based on the use of a material, such as sisal, with a thermal conductivity similar to that of sawdust. †Based on amortization of loan in equal yearly installments.

considered, for example, a village of 300 families has a 500-kW supply continuously available, much more than it can reasonably use on a continuous basis. A more reasonable load factor to assume would be 0.1, which would make the transmission costs 0.58s/kWh. With the average generating cost in the existing grid 0.30s/kWh, the cost for delivered electricity by this scheme would be 0.88s/kWh—a figure comparable to current consumer prices in Dar es Salaam. This modest cost, it must be remembered, would be available only to those fortunate few villages within 20 km of the existing grid—assuming, of course, that TANESCO would be willing to sell electricity to the distribution point for its cost of generation. A more realistic estimate would take into account the cost of transmission to the distribution point, but this information was not available to the panel.

Small-scale diesel generation. In view of the ubiquity of diesel electric generators, it is instructive to examine the cost of generating electricity by this technology. Table 11 summarizes the cost figures based on current retail prices in Dar es Salaam. At a cost of 2.3s/kWh for diesel-generated electricity, it is apparent that, with the exception of photovoltaics at present prices and biogas-generated electricity, the alternative technologies considered in our discussion would be preferable on a unit-cost basis. Even photovoltaic devices will be preferable in a few years.

Table 10. Cost of supplying electricity from existing grid.

Base data	
Grid voltage	33 kV
Distance from grid to village (assumed)	20 km
Distribution voltage to substation	11 kV
Local distribution voltage	400 V
Number of substations assumed*	45
Average hook-up distance for 45 substations and 300 families in 16-km² village	0.2 km
Fixed costs	
High voltage step-down transformer	
33 kV to 11 kV, 500 kW at 1,000,000s/500 kW	1,000,000s
11-kV transmission line 20 km at 500s/km	10,000s
Substation transformers	
11 kV to 400 V, 50 kW at 10,000s/50 kW	450,000s
Local distribution lines (400 V); 300 families at 0.2 km per family and 12s/m	720,000s
Fixed costs	2,180,000s
Financing† costs	
2,180,000s at 10 percent for 20 years	256,000s/year
Cost of electricity‡	
Total annual capacity, 500 kW × 8760 hour/year	4,380,000 kWh
Unit cost of capacity (load factor = 1)	0.06s/kWh
Unit cost at 10 percent load factor	0.58s/kWh

*Because local distribution is so expensive, in this example it is cost effective to underutilize the substations by using many of them to reduce local hook-up distance. †Based on amortization of loan in equal yearly installments. ‡This calculation represents the unit cost of transporting electricity from the 33-kV transmission line to the consumer. It does not take into account maintenance costs for the system nor the cost of electricity delivered to the point where the 11-kV line starts.

Table 11. Cost of supplying electricity by small-scale diesel generators.

Base data	
Operation	5 hour/day
Useful life (about 10 years)	20,000 hours
Fuel consumption	0.35 liter/kWh
Overhaul	every 5,000 hours
Fixed costs	
Retail cost, 6-kW diesel generator	29,000s
Overhaul costs	15,000s
Installation	2,900s
Annual costs	
Equipment and installation, 32,000s at 10 percent for 10 years*	5,200s/year
Overhaul, 15,000s at 10 percent for 3 years*	6,000 s/year
Maintenance, operator	7,000s/year
Total annual costs (less fuel) (approximate)	18,000 s/year
Cost of electricity	
Total energy generated annually	11,000 kWh
Unit cost, less fuel	1.6 s/kWh
Fuel cost, at 2s/liter	0.7s/kWh
Total unit cost	2.3 s/kWh

*Based on amortization of loan in equal yearly installments.

One of the problems with such solar energy technologies that depend on wind or sunshine or even flowing streams is that these are intermittent sources of energy, so that in the United States they require a backup system based, for example, on gas, oil, or electricity. The cost of the solar-based system plus the backup system may be prohibitive. However for many village tasks in the developing countries, the backup system may be the traditional energy system. If the wind fails to pump water, the villagers simply revert to carrying it on their heads. If the sun fails to shine to refrigerate fish, they are smoked over a wood fire, and so on. Moreover, a number of tasks can be performed whenever primary energy is available—for example, grain can be ground or water pumped and then stored for later use.

Thus far we have established that there are good technologies, that there is preliminary evidence that some of them may be cost effective and that, in many cases, there is a ready backup system that entails no capital costs. But there is still very little experience with installing such technology in rural villages of the Third World under circumstances where good cost and performance data have been kept. In fact, many of the experiments in placing technology in villages have ended in failure. A number of windmills and a few methane digesters have been tried in African villages, for example, with far from encouraging results. Outside technicians came into the villages with a preselected technology to perform a preselected village task, and without very much interaction with villagers they erected and operated the energy-producing hardware. A few weeks or months later, the visiting technicians left and shortly afterward the technology fell into disuse. But this pattern is not unique to small-scale renewable energy hardware. Whether it be farm machinery, or transport or construction equipment, to provide such capital goods to a village without first training a cadre of people able to operate, maintain, and repair it, and without ensuring that there is local institutional infrastructure to support it, has universally proved to be futile. The latter might be a government institution such as a school, or a cooperative society, or a private entrepreneur. Without trained people and a responsible institution the chances are that energy technology will not be properly or long used. To give such technology a fair chance for success, it is necessary to enlist the enthusiastic cooperation of appropriate villagers. This means villagers must be involved in selecting the village task to be energized, in selecting the technology, and in determining what village institutions should be responsible for its maintenance and use.

The subject of finding renewable energy sources for Third World rural areas is not just a matter of humanitarian concern for those people. It may directly affect the availability of world energy supplies. Third World rural areas are not significant commercial energy users at present. However, influential leaders in the international community have set a target of eliminating the worst aspects of absolute poverty by the end of the century. The Overseas Development Council has examined the energy consumption of the 25 developing countries that have largely achieved this target to gauge what might happen to energy demand if all developing countries were to do so. Three preliminary important conclusions appear warranted. First, those nations (such as Brazil and Mexico) that have emphasized growth alone are relatively much higher per capita energy users than those countries (such as Taiwan) that have pushed growth with equitable distribution of incomes, or those (such as Sri Lanka) that have focused exclusively on equitable income distribution and have not made such headway on growth. Second, even if all Third World countries follow the relatively energy efficient growth with equity strategy, the goals of eliminating the worst aspects of absolute poverty cannot be met without imposing a claim on world oil resources larger than world oil production will permit. Third, therefore these development goals can only be met if nonpetroleum sources of energy are made available to these rural areas. Under these circumstances, exploring the use of small-scale renewable sources of energy appears to be an attractive path.

References and Notes

1. V. Smil, *Bull. At. Sci.* **23** (No. 2), 25 (1977).
2. The U.S. team, in addition to the authors of this article, included Dr. J. R. Williams, associate dean for research, College of Engineering at the Georgia Institute of Technology; Dr. T. Lawand, director of field operations of the Brace Research Institute, McGill University, Montreal, Canada; Dr. B. Williams, director of the Energy Systems Research Laboratory of R.C.A.; and Dr. P. Reining, Office of International Science of the AAAS. The Tanzanian participants included representatives from the sponsoring council, the Prime Minister's office, relevant ministries and interested organizations, and the University of Dar es Salaam.
3. Calculations such as those in the following pages will be included in a forthcoming NAS publication on the proceedings of the workshop. Although these calculations are based on the work done at the NAS workshop, the particular numbers in this article are those of the authors and have not been checked yet with other members of the workshop.
4. The rate is 0.93 shilling per kilowatt hour. Actually the rate is graduated according to the amount used. The exchange rate is approximately U.S. $1 = 8.2 shillings.
5. The estimates made by the panel for the renewable resource technologies aimed at producing electricity as well as for diesel did not include the cost of power distribution in the village. Such costs are treated in the discussion of extending grid to the villages.
6. In view of the uncertainities in the cost estimates, all numbers are given only to two significant figures.
7. World Meteorological Organization, average of data for June 1966.
8. In this analysis, and those to follow, the cost of generating electricity is compared with the current price to the consumer. The principal justification for this approach is the assumption that the communal nature of the Ujamaa villages lends itself to eventual communal ownership of the generating system—hence the important datum for the villagers is the energy cost.
9. National Academy of Sciences, *Energy for Rural Development* (National Academy of Science, Washington, D.C., 1976). See "Hydropower" in part 2, *"Indirect Uses of Solar Energy,"* for a discussion of the growing use of small-scale hydroelectricity in the People's Republic of China.
10. Tanzanian participants thought that this was reasonable since village labor and materials would be volunteered and hence would not need to be included in the funds budgeted for the project. In a similar situation, techniques in which local labor and materials were used to construct dams and penstocks for installations capable of producing power in tens of kilowatts have been developed in Colombia at the Centro de Desarrollo Integrado "Las Gaviotas."
11. See *Methane Generation from Human, Animal, and Agricultural Wastes* (National Academy of Sciences, Washington, D.C., in press).
12. P. S. Mhina, "A brief description of manufacture and utilization of gobar gas in Tanzania," presented as a Seminar on Appropriate Technology in Small-Scale Industries, 15 to 17 December 1976, Dar es Salaam Technical College [Small Industries Development Organization (SIDO), Box 2476, Dar es Salaam]; A. Mzee, *Pilot Project on Utilization of Gobar Gas in Small I.C. Engines* [Ministry of Water, Energy and Minerals, P.O. Box 9153, Dar es Salaam, Tanzania (1977)].
13. P. Fraenkel, *Food From Windmills* (Intermediate Technology, Ltd., London, 1975).

The CANDU Reactor System: An Appropriate Technology

CANDU combines a proved reactor, a simple industry, and outstanding potential for resource conservation.

J. A. L. Robertson

The Canadian CANDU (Canada Deuterium Uranium) power reactor does not fit easily into categories of U.S. reactors. Pickering nuclear generating station, which is operated by Ontario Hydro and consists of four 500-megawatt (electric) CANDU reactors, has produced more electricity than any other nuclear generating station, at roughly half the cost of electricity from the available alternative, a coal-fired plant. CANDU reactors are therefore "currently commercial," and comparable to the U.S. light-water reactors. In the United States, however, heavy-water reactors, along with molten-salt and high-temperature reactors, are usually considered as "advanced" because of their low uranium consumption. Neither description does the CANDU reactor full justice. Good neutron economy gives CANDU reactors the ability to operate on a thorium fuel cycle at, or near, breeding. This means that the energy costs are virtually independent of the fuel supply cost, making CANDU comparable to the fast breeder reactor. As a commercially proved reactor able to adapt to changing circumstances, CANDU has a useful role to play in the world's future energy supply.

To a physicist, the essence of a CANDU reactor is its use of heavy water as the moderator. In any thermal reactor the moderator must slow down neutrons efficiently while capturing as few as possible. Both requirements are factored into a figure of merit called the moderating ratio. Table 1 shows how heavy water stands out from other potential materials. To an engineer, pressure tubes are

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