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Sustainable, efficient electricity service for one billion people^[1]

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A partnership of affluent nations is proposed to pursue the objective of universal electrification in the world with a challenging interim goal of bringing efficient and sustainable^[2] electric services within 20 years to one billion people. Four plausible partners are the United States, the European Union, Japan with Australia and New Zealand, and, perhaps, the OPEC countries.

The partners would provide part of the capital needed for electrification. This “concessionary” contribution should stimulate private investors and/or indigenous governments to supply the remainder of the capital needed, and to organize the management of each electrification project. The concessionary contribution would be designed for two objectives: (1) to help alleviate poverty, grow opportunities, and increase the quality of life in the developing world by providing electric services to all, and (2) to reduce future greenhouse gas emissions by supporting a low-carbon development path toward universal electrification.

Paying for the difference in cost between high-efficiency end-use equipment and least-first-cost equipment would pursue the first objective. This concession would significantly lower the cost to the consumer of electricity services. The second objective would be pursued by paying the added cost (up to \$ 1000/kW) of low-GHG or climate-friendly electricity generation (i.e., low or no-net carbon-emitting systems) over and above least-first-cost generation technology.

This electrification of one billion people would require about 50 GW_e of new electric generating capacity assuming 50 % capacity factor and 15 % line losses. The concessionary investment needed would be up to \$ 50 billion for low-GHG generation plus about \$ 30 billion for efficient end-use equipment. An additional 25 % of the concessionary contribution would go for training, program management and evaluation. The total is \$ 100 billion (or \$ 100/person) spread over 20 years, or about \$ 1.25 billion per partner per year assuming an equal share for each partner.

The remainder of the capital required is estimated to be about \$ 170/person for the electrical system including hook-up, plus another \$ 140/person for efficient end-use equipment purchased at the cost of least-first-cost equipment. The consumer would pay back these non-concessionary investments through the price of electricity and through a lease-purchase charge for end-use equipment.

Provision of basic electricity services for newly electrified communities is estimated to require about 0.025 kW/person on average for all electric uses including domestic, commercial, agricultural and industrial uses, compared with current electricity services of about 1.8 kW/person in the United States and 0.3 kW/person globally. Thus, electric power per capita in these poor, mostly rural areas would be very small initially, just sufficient to meet basic necessities, and consistent with customers’ ability to pay.

Not every community would choose or be able to buy even this much, but to have the opportunity for electric services at whatever level will make a huge difference in people's lives. Experience over many decades has shown that electrification can help alleviate poverty, improve health, reduce drudgery, and increase literacy, all contributing to the UN's Millennium Development Goals to which all countries are committed.

1. Introduction

The IEA [2002] has recently described the energy problems of the poor. It points out that about 1.6 billion people – one quarter of the global population, many living on less than \$ 2 per day – have no access to electricity. IEA estimates that although electrification is progressing at a strong pace, by the year 2030 there will still be some 1.4 billion without electrical services. This is despite an electrification rate averaging as much as 80 million people per year over the past three decades. More than half of this electrification has been in China and other East Asian countries.

Electricity offers such flexibility and variety in end-use services that it is widely recognized as an energy form that serves as a key ingredient underpinning economic development and improving the quality of life^[3]. In the early and middle parts of the last century, the importance of electrification as a driver for economic development was broadly and enthusiastically accepted^[4]. In the latter part of the century, studies examining the relationship between electrification and economic growth asserted that such enthusiasm was misplaced: electrification by itself was not an automatic and sufficient driver of economic growth, particularly if other key factors for such growth were absent [World Bank, 1995]. Subsequent studies, however, have reassessed this question in the light of meeting essential needs for human development (e.g., improved health and literacy) as well as economic development (e.g., industrial facilities and related infrastructure). These more recent studies (discussed below) give strong support to the view that electrification confers substantial benefits and substantially improves human well-being and overall development.

Recently, for example, the Human Development Resource Centre in Dhaka, Bangladesh, has tried to measure carefully the economic and social impacts of rural electrification since 1978 [Barkat et al., 2002]. This electrification was pursued with the assistance of the National Rural Electrification Cooperative Association International. The study showed that electrification is strongly associated with higher family income (65 % higher than for non-electrified villages). 16 % of annual income of electrified households is attributed to electricity. Electrified local industries employ 11 times as many workers as non-electrified industries. Literacy rate was 71 % for electrified villages compared to 56 % for villages without electricity. Human health was improved; for example, infant mortality was 43/1000 for electrified households compared to 58/1000 for households without electricity. Immunization was 61 % compared to 37 % for non-electrified villages. Electricity also contributed to empowerment of women, and it significantly improved agricultural

and industrial productivity and stimulated commercial activities.

Similar results were reported in a recent World Bank study in the Philippines [World Bank and IDPMRF, 2002] that compared villages matched in demographic and socio-economic aspects. One set was electrified and the other remained unelectrified. Significant benefits are attributed to electrification such as, “less expensive and expanded use of lighting, radio and television; improved returns on education and wage income; time-saving for household chores; and improved productivity of home businesses”. The population regarded these benefits as of such high value that they considered electricity costs as high as 10 % of family income to be affordable.

An important conclusion from the report is:

“Even in its role as a pilot study, this report reaches an overall conclusion that appears reasonably robust. The strong desire of most developing countries for electrification can be quantified in monetary terms. Even if the preliminary Philippine benefit numbers exceed what would be representative of many developing countries, they do raise the real possibility that, in the long term, benefits will outweigh the costs of extending electricity services even for the poorest populations. If this is the case, the Bank should focus on overcoming the high initial costs of newly implemented programs. While subsidies may be necessary to overcome first-cost problems arising during the capital-expansion phase, this study's results suggest that long-term subsidies are unnecessary because of rural residents' willingness to pay the costs of electricity services.”

In addition to empirical evidence, theoretical arguments have also been made suggesting that electrical services are important to driving economic development. Ayres and Warr [2002] conclude that electrification is not merely an outcome of development, but it is also a factor contributing to development. Electrification is a driver for development, just as increasing prosperity from development drives electrification.

Of course, electrification is not a panacea for poverty, since other conditions must be satisfied in order to take advantage of the benefits access to electricity offers. Empirical evidence from China, for instance, suggests that electrification provides greater poverty-alleviation benefits to communities that are just below the poverty line than to those that are extremely poor [Yang, 2003].

Many organizations, public and private, are working diligently for universal electrification^[5]. Nevertheless, as IEA observes, more aggressive actions are needed. So, what is the problem? Electric systems including end-use technologies are very capital-intensive. Most of the people

without access to electric services are rural poor. They don't have capital or easy access to it. Even if electricity is available, least-first-cost and generally inefficient end-use equipment substantially raises the cost of electricity services. Furthermore, many (if not most) of the electricity utilities in the developing countries are poorly managed, and many are in dire straits financially. Helpful intervention on the consumer side of the meter is rare. Can anything else be done?

This paper describes one possible collaborative action that could be taken by concerned affluent nations. It should be noted, however, that electricity is not the only energy problem of the poor. A very comprehensive review has recently been prepared for the Millennium Development Project [Modi, 2005]. Also Goldemberg et al. [2004] have proposed a clean cooking fuel initiative. Both electrification and clean cooking fuels (and transportation) are important and in fact, they are coupled in some ways. For example, electric flue fans for solid fuel stoves can improve efficiency and reduce indoor air pollution [Heltberg, 2004]. Here the focus is on electrification because it is necessary, even if not sufficient.

2. The goal

The goal addressed by this paper is universal electrification^[6] with an interim objective of electrifying one billion people in twenty years. It is argued that such a goal is achievable if it is undertaken by a collaborative group of affluent industrialized countries.

Why might the developed world take on this mission? The following are important reasons, some of them inter-related.

First, as discussed above, electrification of some of the poorest people in the world should stimulate their economic development and vastly improve their quality of life. In a world where diseases originating in the poorest countries can infect populations in rich countries, and where access to products and markets of poor countries can impact the macroeconomic health of wealthy nations, economic development of these regions has consequences well beyond the confines of villages. Most importantly for the poor of the world, electrification can be an essential stimulant to their economic and human development.

This initiative may contribute to global stability and thereby promote security. The gap between the rich and poor, both between countries and within the developing countries themselves, is a continuing source of stress. To the extent that electrification raises the standard of living of the poorest on the planet, that stress is moderated. Improving the living standards of the poorest will also help advance other relevant Millennium Development Goals (MDGs) of the United Nations regarding extreme hunger, clean water and sanitation, literacy, health and the environment^[7].

Second, achieving sustainable electrification in the developing world in ways that have low or no net carbon emissions is a necessary part of global climate stabilization. Electrification of one billion people using sustainable low or no net carbon-emitting technologies, although

modest in its near-term contribution to controlling global carbon emissions, can help develop and incubate technologies that may have a much larger impact. The proliferation of sustainable electric systems and efficient end-use technologies should stimulate innovation and economies of scale that will bring down the costs for all, including wealthier nations, thus reducing the costs of carbon-neutral energy systems and permitting their deployment sooner than otherwise.

Third, this mission will provide incentives and opportunities for many entrepreneurs as well as philanthropic organizations in both the developing and the developed world, and it should stimulate important interactions and partnerships that promote goodwill in a terrorism-plagued world. Among these opportunities will be expanded markets for advanced electric technology including more efficient end-use equipment. The partners themselves will no doubt meet a substantial portion of the demand for such technologies, often in collaboration with the developing countries that are served.

3. The proposal

Although one can imagine many variations, the following is the core of what is proposed.

Suppose for example that four partners, the European Union, the United States, Japan (perhaps with Australia and New Zealand) and OPEC, took on the mission collaboratively. This is just one possible set of partners, but it appears to be a reasonable one. In practice, each partner could likely attract other collaborators and donors.

The mechanism for the allocation of the money would be developed by the four partners in concert with developing nations. One possibility is that each of the partners could choose those nations it would help. Other approaches are equally possible. An international agency would probably be empowered to administer the funds, although it could be done through a consortium of the four partners^[8].

The developing world exhibits great diversity. Each country will be different and will need to be treated as a unique case. The variation will be enormous with respect to culture, geography, leadership, resources, stability and security and the cost of electrification. These variations are the essence of the problem obscured by the use of averages in this paper to estimate costs and other parameters. The partners will need to be very flexible in the design of programs that fit these varying circumstances.

As described later in the paper, the partners would provide part of the capital needed for electrification. This concessionary contribution should yield incentives to private investors and/or host governments to obtain the remainder of the capital needed, and to organize the management of each electrification project.

The concessionary contribution would be designed for two objectives: (1) to help alleviate poverty, grow opportunities, and increase the quality of life in the developing world through advancing towards universal electrification, and (2) to reduce future greenhouse gas emissions. It would achieve the first by stimulating electrification and

by reducing the cost of electricity that the consumer pays for a given electric service. This would be accomplished by paying the additional capital cost for very efficient end-use technology. It is shown below that domestic electricity consumption and hence the electricity bill a family pays can be cut dramatically (50 % in the example below) by very efficient but cost-effective end-use equipment. Of course, the same qualitative conclusion applies to other sectors of electrical consumers. The idea that cost-effective high-efficiency technology is an essential ingredient in least-cost energy services for the developing world was treated in considerable depth in the seminal paper by Goldemberg et al. [1985].

The concessionary contribution achieves the second objective by paying the additional capital cost of providing sustainable electricity generation with low or no carbon emissions. This concessionary contribution is not a new idea^[9], but it has not been practiced on such a massive scale. Furthermore, this concession will help buy down the cost of advanced sustainable generation by providing multiple learning-by-doing opportunities.

In carrying out the mission, the many organizations already actively pursuing electrification, for example, the United Nations Development Programme, the World Bank and the Global Environment Facility, should be engaged for consultation, information, and contacts, and probably for management and operational support as well. Agencies in developing countries that have carried out or are already engaged in rural electrification should be enlisted. Also, the various countries that have participated in planning and designing projects that fall under the auspices of the Clean Development Mechanism (CDM) of the Kyoto Protocol also are accumulating considerable experience in paying for additional costs of greenhouse gas mitigation. Reduction in greenhouse gas emissions resulting from this concession might be credited to the partners (those that are eligible) as a CDM credit under the Kyoto Protocol, for example.

It is presumed, however, that the partners would be in charge and maintain direct responsibility. The partners would set the rules governing the electrification approach and how the concession is managed, and they would monitor progress to make modifications as needed. Provisions should be made for independent oversight to ensure that funds are used as directed and to provide feedback on program performance.

The concessionary contribution must include also money for training of indigenous people in the electrification systems and technologies and in the business of providing electric services, including the provision of efficient end-use equipment. This portion of the concession – including many training, transfer of know-how and other key activities needed to make the investment effective in countries with poorly developed market-based institutions – could easily be as high as 25 % of the capital investment^[10]. Some relevant training and know-how transfer is already going on. For example the US Energy Association manages a program for USAID to bring together utilities in the United States with those in devel-

oping countries around the globe to stimulate knowledge and know-how transfer.

The contribution may also need to fund incentives and opportunities for entrepreneurs in the developing world and in the countries of the partnership. It is important that programs are developed to make raising the remainder of the needed capital from private sources easier. One idea is the global development bond suggested by the Energy Future Coalition [EFC, 2003; Wirth et al., 2003]. Such bonds could be sold under the auspices of the partners and be partially or wholly underwritten by them. The selling agent might be the World Bank. The bonds could be for specific projects or collections of projects in various countries.

Establishing such a partnership and making it work is surely a challenge. Still, the fact that several affluent countries have recently announced target dates for committing up to 0.7 % of their GDP annually for alleviating poverty may be a sign that such a partnership is possible. The estimated cost (see the next section) of what is proposed would be a small fraction of 0.7 % of GDP from wealthy nations.

The partnership could take the form of a treaty worked out in the context of the UN. A treaty would help ensure that the partners remain steadfastly committed to the goal of universal electrification. Various less formal mechanisms for implementing the partnership are also worthy of consideration, since they may be easier to implement.

This is the broad outline of a plausible proposal for accomplishing the goal of universal electrification.

4. Electricity needs of the very poor and the concessionary contribution

How much would the partners need to put up to carry out the mission of electrifying one billion people, most of whom are poor and live in rural and sometimes remote areas? How much electricity must be generated, transmitted and distributed, and what would be the capital cost? What would be the price of electricity to consumers? These questions have no exact answers, but plausible ranges can be estimated.

We estimated electricity demand from the bottom up, starting with domestic needs of an average family of six. The results of this approach are shown in Table 1. Here the energy demand for various electric services such as lighting, refrigeration, electric fans, television and sewing is estimated. The left-hand side of the table gives the estimated power use and capital cost for state-of-the-art high-efficiency equipment. The right-hand side gives the estimated power use and capital cost for the least-first-cost equipment for the same service as on the left. Estimated total domestic power use is 0.012 kW/person and 0.023 kW/person for the efficient and less efficient cases, respectively (105 and 201 kWh/year-person)^[11]. We note that a small amount of electricity can go a long way, particularly if efficient end-use equipment is used.

The example given in Table 1 illustrates a vital point. Efficient end-use technology can cut electricity use dramatically, in this case nearly 50 %. (Of course, this percentage

Table 1. Estimated capital and energy costs for household electrical services

Equipment (units per household)	Efficient technologies				Least-first-cost (LFC) technologies			
	Total capital cost (US\$)	Power demand (kW)	Usage (hours/day)	Daily energy use (kWh/day)	Total capital cost (US\$)	Power demand (kW)	Usage (hours/ day)	Daily energy use (kWh/day)
Refrigerator ^[1] (1)	278	0.018	24	0.42	212	0.041	24	0.99
Light fixtures (2)	6				6			
Bulbs ^[2] (2)	10	0.040	5	0.20	1	0.120	5	0.60
TV ^[3] (1)	90	0.007	4	0.18	90	0.009	4	0.23
Fans ^[4] (2)	30	0.060	10	0.60	20	0.120	10	1.20
Sewing machine ^[5] (1)	50			0.20	50			0.20
Other ^[6]	50			0.10	50			0.10
Total (per household)	514			1.70	429			3.31
Total (per person)	86			0.28	71			0.55

Estimated financial indicators	Efficient technologies	Least-first-cost (LFC) technologies
Assumed unit cost of electricity (see text)	0.10 US\$/kWh	0.10 US\$/kWh
Average household size ^[7]	6 people	6 people
Annual expenditure on electricity per household	62.2 US\$/year	121.0 US\$/year
Total annual expenditure per person ^[8]	20.1 US\$/year	29.9 US\$/year
Electricity savings per person (LFC – efficient)	0.27 kWh/day	
Concessionary capital contribution per person (efficient - LFC)	14.2 US\$	
Annual electricity cost savings per person due to efficient equipment	9.8 US\$	
Simple pay-back time ^[9]	1.4 years	
Time for electricity savings to equal capital cost (without interest) ^[10]	7.3 years	
Time for electricity savings to equal capital cost (with interest) ^[11]	9.9 years	

Sources: Jannuzzi et al., 2002; USDOE, 2002; Murthy et al., 2001.

Notes

1. Differences between LFC and efficient cases are based on an engineering-economic study of the most popular model in Brazil, a single-door, 330-liter domestic refrigerator with small freezer compartment inside the refrigerator space [Jannuzzi et al., 2002]. Assumptions in this table about equipment, while based on empirical data, should be considered indicative only.
2. Here we assume two light fixtures per household. LFC: two 60 W bulbs used two at a time (replaced when burned out) five hours/day each, approximately 800-hour life. Efficient: two 20 W CFL bulbs used five hours/day each, 10,000-hour life [USDOE, 2002]. Because of the difference in lifetime between CFLs and ordinary incandescents, twelve incandescent bulbs are assumed to be used in series in the LFC case for each CFL used in the efficient case.
3. LFC: typical new, US, 13" screen color TV, energy use estimated as 50 % of 25" screen TV. Efficient: proposed EnergyStar standard, 1 W stand-by power draw, US, 13" screen color TV, energy use estimated as 50 % of 25" screen TV [USDOE, 2002; US retail websites]. Difference in efficiency between the two cases is due to difference in stand-by power draw, an essential costless change that would be implemented by manufacturers responding to efficiency standards. There would be program costs associated with the standards, but this would not affect retail cost. Daily usage is from mainly rural households in India with 5 A connections [Murthy et al., 2001]. Total daily energy consumption in each case is a weighted mean of in-use consumption and stand-by consumption.
4. LFC: 60 W fans, annual average use of 10 hours/day. Efficient: assume savings equivalent to US ceiling fans with more efficient motors and blades (50 %) at a 50 % cost increment [USDOE, 2002]. Since there is great regional variability in hours of fan use, we have chosen an intermediate value of 10 hours use per day.
5. Both cases are assumed to be the same, since significant energy savings in sewing machines would be relatively expensive. In some areas, sewing machines may not be common, but this is included as an explicit example of the types of other appliances that newly electrified households could be expected to use.
6. This is a miscellaneous, unspecified category. The range of other electrical appliances used varies widely among regions and households, and includes such items as battery-chargers, small appliances such as irons, cooking equipment, audio-visual, electronic, and communications equipment, washing machines, and water- and space-heaters. Some uses of electricity, such as small electric fans for combustion chambers in solid fuel cookstoves, may lead to improved efficiency in use of household solid fuels, as well as major health benefits, from reduced indoor air pollution.
7. Calculations are for a generic family of six.
8. Efficient: annual expenditures per person for electricity services (capital plus electricity) with concession that subsidizes the difference in capital cost between LFC and efficient equipment. Capital equipment costs paid by households are financed over 10 years at 6 % annual interest, and households pay full annual electricity costs. LFC: annual expenditures per person for electricity services, including full capital costs of equipment, financed over 10 years at 6 % interest, plus full annual electricity costs.
9. Calculated as the difference in capital cost of LFC vs. efficient equipment divided by the value of annual electricity savings.
10. This gives the number of years it would take for the electricity savings from using efficient equipment to match the subsidized capital cost of the efficient equipment (\$ 429/household).
11. This is the same as the previous row, except that it assumes that the efficient equipment is purchased at the subsidized price with a ten-year loan at 6 % interest (\$ 583/household).

will depend on the mix of end-use technologies chosen by the consumer.) Consequently, for the same services the consumer pays half as much in electricity costs. We assume that the extra capital cost of the efficient equipment is paid for by the partners. The reduced electricity cost is a direct saving for the consumer. For the case in Table 1, the added cost of the efficient equipment (without the concession) would have a simple pay-back in electricity cost savings of less than two years if the price of electricity were 10¢ per kWh.

This is just the electricity needed for the domestic sector of the economy. Electricity must also be supplied for commercial, industrial and agricultural activities, and for community needs such as water purification and pumping. In Bangladesh, such end-uses demand about as much as the domestic sector [Barkat et al., 2002]. At the start of rural electrification in 1983 only 22 % went for domestic uses, however. In other parts of the developing world with more robust economic development under way, non-domestic use exceeds domestic use by a factor of two to three. We use the smaller number, from Bangladesh, assuming it to be more representative of economic opportunities and conditions for the world's poorest one billion people.

Efficiency can have the same qualitative effect on the demand for non-domestic uses as well. It is proposed that the partners provide for the added capital cost of high-efficiency equipment for these uses also. However, the added cost is unknown. For simplicity it is assumed that these business activities use high-efficiency equipment, thus cutting electricity use by 50 %, and that the extra cost is the same as for the domestic uses. In a study of electricity demand growth in Maharashtra state in India, savings due to efficiency improvements in the industrial, agricultural and commercial sectors were estimated to be at least twice as large as for the domestic sector [Sant and Dixit, 2000]. This provides some justification for our assumption that the potential savings for the non-domestic sectors can be at least on a par with those of the domestic sector. In the Maharashtra study, the total (domestic plus non-domestic) cost-effective electricity demand savings were estimated to be about 37 %. This 37 % was derived assuming a required pay-back of three years or less for the extra cost of efficient end-use equipment. In our proposal the extra capital cost of high-efficiency end-use technology is paid by concession and we assume a 50 % energy saving is plausible.

The Maharashtra study illustrates the point that efficiency is a vital component of least-cost system development. It is an example of the so-called "DEvelopment- Focused, END-Use-directed, Service-oriented or DEFENDUS strategy described by Reddy et al. [1991]. They were among the first authors to illustrate how the adoption of efficient technology could reduce the cost of energy system expansion in the developing world. The question not answered is how to get efficient end-use technology adopted. The concession helps solve this problem by eliminating the first-cost penalty for efficient equipment.

To complete our accounting, we note that about 16 %

of electricity generation is lost in transmission and/or distribution in Bangladesh [Barkat et al., 2002]. While we acknowledge that line losses can be higher, in some cases as high as 40 % [IEA, 2002], here we assume losses of 15 %.

The total (i.e., domestic plus non-domestic) demand for electricity is about 210 kWh/year-person. After accounting for line losses, this translates into demand for generation of about 240 kWh/year-person. The generation capacity must be more than this to account for peaks in demand and for generator servicing. We assume a 50 % capacity factor, low by the standards of large central power stations but high for small-scale dispersed generation systems, whether fossil or renewable [IEA, 2004]. The required gross generation capacity is thus 0.056 kW/person. For one billion people this is 55 GW of power generating capacity.

From these assumptions we are able to estimate of the size of the concessionary contributions needed. In generation, we estimate that the concession is less than or equal to \$ 1000/kW, and we use conservatively the \$ 1000/kW value. We derive this from examples of low-carbon-emitting systems compared to least-first-capital-cost generators (usually diesel-powered). For example, Hendrick and Williams [2002] calculated the cost of electricity at \$ 0.042/kWh for a Chinese village using crop residue gasification for electricity generated by a microturbine. If operated as planned, this system would have zero net emissions of CO₂. This system had an estimated capital cost of \$ 850/kW compared to \$ 243/kW for diesel generation, but the cost of electricity was half because of the high cost of diesel fuel compared to the cost of biomass fuel. Such a system can be expanded to provide producer gas for cooking and hot water-based district heating. Thus, in this case the added capital cost would be \$ 607/kW. In this case the fuel costs make electricity from the sustainable biomass system less expensive than the diesel fuel oil system. This is, of course, exactly the point of the concession. It is to make the up-front capital cost low enough that good sustainable systems will be built, and the world will learn from the experience and take advantage of the opportunities.

For low-GHG generation then, we estimate the cost of the concession to be up to \$ 55 billion or \$ 55/person.

The concession for efficient end-use equipment is estimated from Table 1. It shows the added cost of efficient equipment to be \$ 85 for a family of six or \$ 14/person. If an equal amount is assumed for the business sectors, the total concession for efficiency is \$ 28/person or \$ 28 billion. We believe this estimate may be high for some regions, depending on demand for electricity services among the rural poor. In Bangladesh, for instance, the concession would be significantly less.

The total is up to \$ 55 billion for low-GHG generation plus \$ 28 billion for high-efficiency end-use equipment plus 25 % for program costs, training and transfer of know-how and creation of markets and institutions to deliver and support electricity and efficient end-use adoption. This sums up to about \$100 billion over 20 years.

The total concession would be up to \$ 5 billion/year or \$1.25 billion/year for each partner. We note, however, that the use of efficient end-use technology would reduce the power generation requirement perhaps by half along with reducing annual costs of electricity.

Sharing this concession of \$ 5 billion/year four ways, with each partner providing \$1.25 billion/year (or about one-tenth of the current level of US official development assistance), is perhaps a way to make the cost more affordable to each^[12]. This equal sharing may not be acceptable because of differences in GDP, for example. The partners would need to agree on the equity issue.

The working together by the partners on this mission may in itself have unforeseen positive consequences in promoting collaboration and improving world stability.

5. Additional capital needed

The largest share of the capital to be raised is over and above the concession. The IEA has recently made estimates of the capital required for electrification [IEA, 2003]. It estimates that the average capital cost of the supply infrastructure for unelectrified populations is about \$ 3100/kW, presumably for conventional least-first-cost technology^[13]. This is for an average generation capacity of about 0.15 kW/person. Using this cost number, and the generation capacity for our efficient case of 0.056 kW/person, the capital cost of the electric infrastructure systems would be about \$ 3100/kW times 0.056 kW/person, or about \$ 170/person. This includes the cost of generation capacity (excluding the concession for low-GHG generation) and of transmission, distribution and hook-up^[14]. Hence, under these assumptions the balance of generation, transmission and distribution capital that must be secured is \$ 170 billion over 20 years, or about \$ 9 billion /year. If these one billion people, on the average, make \$ 0.50/day, then their aggregate annual income is \$ 180 billion/year. We cite this with reference to the willingness expressed by poor villagers in the Philippines to pay up to 10 % of their income for electricity services [World Bank and IDPMRF, 2002]. This places in context the \$ 9 billion estimate above.

The consumers, through the price paid for electricity, must ultimately supply this capital. The partners would presumably work with the host countries and private or philanthropic investors to persuade them to put up the money, and to operate the resulting electric systems on a pay-as-you-go basis. The up-front capital might also be supplied by private investors through the purchase of global development bonds described earlier with the partners underwriting some or all of the investment.

It should be noted, however, that the capital charges alone (assuming the IEA estimates are reasonable) would amount to about \$ 0.06/kWh if the capital were paid back in 20 years at 6 % interest. To this must be added the cost of fuel and the costs of operating, maintenance and management plus losses in transmission and distribution, plus a profit if the utilities are operated for profit^[15]. In this paper the price of electricity at the meter is assumed to average \$ 0.10/kWh as a plausible guess.

To this capital cost for infrastructure must be added the capital for least-first-cost end-use equipment. (The partners make up the cost difference between least-first-cost and high-efficiency equipment, of course.) For the example in Table 1, this least-first-cost capital is estimated to be about \$ 70 per person for domestic electricity use, or a total of \$ 70 billion to be supplied by consumers over 20 years.

Thus, the additional capital that must be raised over and above the concession is about \$ 170/person for the electric infrastructure plus \$ 140/person for end-use equipment (domestic and industrial), or \$ 310/person total. The equivalent investment for the least-first-cost (LFC) case (without high-efficiency technology) would be \$ 340/person for electric infrastructure plus an assumed \$ 140/person for least-first-cost end-use equipment for a total of \$ 480/person. The price of electricity for consumers would be about the same in both cases, but the electricity consumption, and correspondingly the expenditure for obtaining the same electricity services, will be less for consumers in the efficient case by a factor of about two. Domestic consumers using the average amount of electricity indicated in Table 1 would pay about \$ 10/year-person with efficient end-use equipment instead of \$20/year-person with inefficient equipment, assuming the price of electricity is \$ 0.10/kWh.

Efficiency clearly can make a big difference.

6. Affordability

Assuming that the average family can purchase its domestic high-efficiency end-use equipment at least-first-cost prices, from the electric utility (or other supplier) at 6 % interest, and that the capital is paid back in 10 years on average, the cost would be about \$ 10/year-person.

Including the earlier estimate of about \$ 10 per person per year for domestic electricity services, the total cost would be \$ 20/year-person.

If, however, least-first-cost end-use equipment were used, the electricity cost would be double for the same electrical services, bringing the total to about \$ 30/person per year. The electricity cost savings significantly increase affordability. Similar savings are expected for non-domestic uses.

The target populations are among the poorest in the world. Are these costs affordable? Where average income is \$ 1/person-day, electricity costs would represent about 5 % of family income for a family of six. The cost of electricity alone would be about 3 %. If total family income were \$ 1/day these costs would be much too high. In Bangladesh the average electrified rural household (6 people) pays only about \$ 36/year for electricity purchased at about \$ 0.06/kWh or about 2 % of household income of \$ 1600/year. Average household income is \$ 0.7/person-day for electrified households [Barkat et al., 2002].

Nevertheless, providing the possibility of universally supplied electricity may allow even the poorest to enjoy some electric services. Not every customer may choose or be able to afford the range indicated in Table 1. Many

may choose to purchase much less at first. The demand will grow quite naturally, with increasing affordability resulting from development, once the infrastructure is in place. It will make a huge positive difference in the lives of those electrified.

7. Sustainable sustainability

Once these sustainable systems are introduced, can they be maintained beyond the period of concessionary contributions? We believe the answer is "Yes" if the electricity systems are constructed and maintained at high quality. It is generally less expensive to repair and maintain generators than to replace them. If the cost of sustainable systems declines with experience, economies of scale, and through learning by doing as well as by the influx of new products and ideas, then we would expect (the initially subsidized) electric systems to perform well without continuing subsidies. One point of this concessionary investment is to provide a large-scale opportunity for trying several things and finding those that work well. For such a system to be economically sustainable, the program needs to be carried out flexibly and with consideration to the long term. This is another of the reasons that we have included 25 % of the concessionary funds as "soft money", e.g., funds for training, education, monitoring, etc., not for hardware purchases.

Nevertheless, typical sustainable systems (as defined in this paper as low-GHG-emitting) may remain more expensive than fossil fuel systems unless the latter are taxed or otherwise constrained. Without the concessionary contribution from the developed world, it will be extremely difficult for developing countries to raise the extra money for sustainable systems unless, by the time for system expansion, the cost has come down, and the need for low-GHG generation appears compelling even from the perspective of a poor country.

8. Conclusions

The goal of universal electrification for the poor of the world starting with one billion people who have no access to electricity is a daunting but feasible mission. Achieving this goal is critical to accelerating development and providing opportunities for transition out of poverty. It can be accomplished in twenty years through a partnership of affluent nations. Not only can it be achieved, but the task can also be managed in such a way that resulting systems are both efficient and sustainable in the sense of having no or low net emissions of greenhouse gases. Perhaps the most important conclusions are that the cost of electricity to the average consumer can be lowered significantly if efficient end-use equipment is adopted and that concerted efforts to accomplish this end are important, possible and affordable. The impact of efficiency is not only reduced consumer electricity bills but also lower capital requirements for electric generation capacity.

Sustainability and efficiency can be assured by concessionary contributions from the partners. The concessions would pay the additional capital cost of sustainable generation compared to least-first-cost alternatives. Similarly,

adoption of efficient end-use technology can be assured with concessions that pay the capital cost difference between state-of-the-art high-efficiency equipment and least-first-cost technology. Consumers would be able to purchase the efficient equipment at reasonable interest rates over time, minimizing first cost problems. Finally the concession would include resources for training, management, and evaluation.

Partners can achieve this mission successfully by paying concessionary costs up to \$ 5 billion/year for 20 years (\$1.25 billion per partner per year). This concession will stimulate governments and private investors to provide the balance of the capital and management skills and dedication to make the process work. This balance is estimated at about \$ 16 billion/year (\$ 9 billion/year for electric infrastructure and \$ 7 billion/year for end-use equipment). In addition to concessions, the partners can also stimulate this needed investment by selling and partially underwriting global development bonds.

This paper is a call for leadership and action by a partnership of affluent nations acting in concert with the United Nations as part of achieving the MDGs, with the developing world and with concerned private businesses, other organizations including NGOs and even individuals. ■

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Notes

1. This paper was presented in outline form at the International Seminars on Planetary Emergencies of the World Federation of Scientists, Erice, Italy, August 20, 2003.
2. For the purposes of this paper sustainable electric systems are those that emit low or no net greenhouse gases (GHGs). This requirement is generally consistent with the goal expressed in the National Research Council report *Our Common Journey: a Transition Toward Sustainability* [National Research Council, 1999]: "... that the primary goals of transition toward sustainability should be to meet the needs of a much larger but stabilizing population, to sustain the life support systems of the planet and to sustainably reduce hunger and poverty." The authors believe that the electric systems targeted in the universal electrification proposal of this paper can contribute to the goals of the transition explored by the academy. The partners must assure this contribution, but for simplicity the authors use the criterion of low or no net greenhouse gas emissions from electricity generation to qualify a system as sustainable.
Sustainable generation could be from various renewable sources including well-sited hydro (with positive resettlement of displaced people) or it could be very efficient fossil-fueled generation with low emissions, such as a combined-cycle natural gas plant or a coal plant with CO₂ sequestration. It could be a biomass facility with no net carbon emissions. It could be a nuclear plant with a carefully controlled fuel cycle including safe disposal of radioactive waste. The sizes of sustainable generation systems can vary from very large central facilities to small distributed and even remote technologies.
3. Recently, the National Academy of Engineering listed electrification as number one in a list of the twenty greatest engineering achievements of the 20th century judged on the basis of impacts on the quality of life [Wulf, 2000]. The importance of electricity to economic and technological progress is described also by Schurr et al. [1990].
4. In the United States for example, the Tennessee Valley Authority was established in 1933 and the Rural Electrification Administration in 1935 followed by the Rural Electrification Act of 1936 leading to the establishment of hundreds of rural electric cooperatives bankrolled by the federal government providing the resources to electrify every area of the country. Rural electrification began in the Soviet Union about the same time but using very different methods [Coopersmith, 1993]. The point is that both countries, as different as night and day, recognized the need for government involvement in electrification. Both the US and the Soviet Union looked at the long term in electrification rather than requiring that each system be financially viable from the start. Something

similar is needed now but on a global scale, and what is proposed here is one possibility.

5. These organizations include, for example, USAID, the World Bank Group, the Global Environment Facility (GEF), the UN Development Programme (UNDP) and various private and public sector organizations and the governments of most developing nations.
6. Here universal electrification means that every household, community and business will have access to electric services.
7. See <http://www.undp.org/mdg/> and <http://www.un.org/millenniumgoals/>.
8. Some OPEC countries are not fully electrified, so the first emphasis of this partner should be to complete its own electrification in a sustainable and efficient way. For example, two countries, Nigeria and Indonesia, have some 170 million people without electrical services. These are also the poorest of the OPEC nations. Whether OPEC countries are politically cohesive enough to function as a partner remains to be seen, but they should be given the opportunity.
9. The GEF operates this way through the World Bank and the UNDP. That is, it pays for the extra cost of systems that reduce carbon emissions compared to conventional systems [Hosier and Sharma, 2000]. GEF resources are not sufficient, but GEF experience and knowledge would be invaluable for carrying out what is proposed here.
10. The 25 % represents the "soft costs" of making a major program happen, which have been shown to be essential for making investments in new equipment and infrastructure effective. It provides training for the large number of rural-dwellers who will participate in the construction of the sustainable electricity systems and possibly in the manufacture of the energy-efficient devices. It will fund information programs so that the rural household members will learn how to use electrical equipment, assure that electrical connections are safe, and provide information about borrowing money to pay for some equipment purchases. It will provide sufficient information and education so that the very poor rural areas to which electrification is extended will be able to participate in the economic activity that the electrification and efficient end-use equipment enables and to use the products effectively and safely. The funds will also be spent on overall program administration, with particular emphasis on monitoring, quality control and theft reduction.
11. There is no easy answer to the question of how much electricity is needed. For example, average domestic electricity use in rural Bangladesh is about 95 kWh/year-person or 0.011 kW/person (for those who have access to electricity). Total electrical use averages about 193 kWh/year-person or 0.022 kW/person. This is presumably without high-efficiency end-use equipment. For the inefficient (least-first-cost or LFC) case in this paper, the electric generation is estimated to be about 0.054 kW/person (total electric use, domestic, commercial, industrial and agricultural plus losses) compared to the comparable IEA number of 0.076 kW/person. For the efficiency case, the number is half of this or 0.027 kW/person. The worldwide "average" electricity generation per capita (including direct use in the household and indirect use in commerce, agriculture and other industry, etc.) is five to ten times the amount we have estimated for newly electrifying populations; per capita electrical generation in the United States is 31 to 62 times higher [IEA, 2002]. Modi [2005] suggests that for the very poor electrical lighting should be the principal domestic use, requiring about 75 kWh/family-year (similar to values given in Table 1 for lighting). Modi further suggests that the initial electrification be directed at schools, hospitals and public buildings. This could provide a community with convenient places to charge secondary batteries for household lighting and communication. With such rechargeable very efficient light packs household demand for lighting could be as low as 15 kWh/year-person [Revkin, 2005].
12. At the UN World Summit on Sustainable Development in Johannesburg in 2002, a goal for the developed world of contributing 0.7 % of GDP to reducing the gap between the rich and the poorer countries of the world was suggested. For the OECD countries this amounts to about \$ 140 billion, much more than is actually given. Concessionary contributions are in the neighborhood of \$ 50 billion/y.
13. IEA [2004] considered three types of electric system. One is an extension of the grid to both urban and rural areas not previously reached. This grid extension is assumed to reach about two-thirds of the population. The second is mini-grid systems assumed to serve 32 % of the population. The final part is for stand-alone (isolated off-grid) systems for remote populations. These isolated off-grid systems reach 5 % of the population. The numbers in the text derive from weighted averaging of these three types of system.
14. We note that the infrastructure cost does not scale exactly with power requirements. The T&D and hook-up capital costs will be more or less independent of the power load, but they will vary with the type of system. In our case, with demand per family reduced by energy efficiency, the estimated capital cost of about \$ 170/person may be somewhat low.
15. The cooperative rural electrification model developed in the United States in the 1930s and adopted very effectively by Bangladesh is another model for management of electrification. It would not require a profit.

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