

# **A Vision for Global Electrification**

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The Program on Energy and Sustainable Development (PESD) at Stanford University is an interdisciplinary research program focused on the economic and environmental consequences of global energy consumption. Its studies examine the development of global natural gas markets, reform of electric power markets, and how the availability of modern energy services, such as electricity, can affect the process of economic growth in the world's poorest regions.

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## About the Author

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# A Vision for Global Electrification

David G. Victor<sup>1</sup>

## 0. Summary

This paper is a working draft intended to both set the stage and stimulate discussion at the upcoming EPRI workshop on Global Electrification. The workshop is part of a larger EPRI initiative entitled the “*Electricity Technology Roadmap*,” which explores how electricity can better serve a global society undergoing different stages of economic development. The horizon for the Roadmap, and therefore the workshop, is nominally 50 years out, when global population will probably approach 9 billion people.

The paper looks at the role of energy in the lives of the poorest people in the world, and the changing pattern of energy use as economic development ensues. The data record in this regard is incomplete and often conflicting, although broad trends are discernable. The author approaches the analysis from the bottom up and the top down, using existing micro-level studies of energy use in the home, and macro-level studies of the coupling between energy use, the increasing electrification of energy, and economic development.

A central tenet is the achievement of universal global electrification by 2050, and the benchmark of a minimum level of electricity consumption of 1000 kWh/person/year by mid century. The author builds the case for 1000 kWh/person/year by looking at the existing hierarchy of energy services. At the base of the energy pyramid is cooking and heating in the home, where as much as 90% of the energy budget is consumed in the poorest rural areas. The next levels in the energy pyramid—where electrification usually begins—include lighting, entertainment and appliances. The author’s analysis suggests that at least 250 kWh/person/year is required in 2050 for core electric services that are difficult or impossible to supply with non-electric fuels or energy carriers. Parallel uses outside the home, such as electricity for water pumping and small-scale commercial activity that occurs even in poor rural areas would push this a bit higher. The greatest unknown in setting the target for minimum electricity consumption in 2050 resides in the base of the pyramid, in particular: whether cooking will move away from traditional fuels toward electricity. Problems with the inflexibility and inefficiency of traditional stoves,

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<sup>1</sup> Questions or comments may be directed to [dgvictor@stanford.edu](mailto:dgvictor@stanford.edu). This draft was prepared solely to assist in the formulation of defensible long-term goals for global electrification and for setting R&D agendas that will aid the industry and governments in meeting those goals. It is offered in the context of the larger updating and revision of the EPRI Strategic Technology Roadmap. Steve Gehl, Revis James, Bob Knight, Tom Tanton, Tom Wilson and Kurt Yeager provided helpful comments, and I am particularly grateful to Brent Barker and Lesley Coben for editorial assistance.

and high levels of indoor pollution, would suggest that households will favor electricity for cooking services—if they have access to electric supply and they can afford it. But actual household behavior, such as revealed in recent surveys in South Africa, suggests that households do not spend scarce resources on electric cooking until many other needs—lighting, entertainment, and appliances such as irons—are amply supplied first. The 1000 kWh/person/year target for 2050 seems reasonable in light of the fact that, on average, per-capita consumption of electricity already exceeds this level in over 50% of Chinese provinces.

Looking at electricity trends from a macro-economic point of view shows that in country after country there has been a steady relationship between electric power consumption and economic development. Importantly, those countries with the highest ratio of economic output to electricity input are all in the developing world, pointing out the enormous productivity gains that can be realized by the first few kilowatt hours supplied in an emerging economy. As a harbinger of change for the poorest nations, it is important to note that electrification of the energy supply has grown progressively in the developed world over the last century. It has gone from near zero to roughly 40% of total primary energy consumption in the OECD nations and seems destined to continue on course through this century. It is likely to reach 50-60% or even more of total energy by 2050, depending in part on the speed of electrification in the transportation arena.

On both these dimensions—the household and the macro economy—closer attention to the efficiency of the electric power system from generation to final user offers much untapped potential for decoupling, at least partially, the level of economic activity from the total quantity of electricity consumed.

The historic lockstep relationship between electricity use and economic development does not indicate simple cause and effect. The author makes the case that economic development is the precursor to electrification, and not the other way around. In exploring strategies for electrification, he contends that the epicenter of policy making must focus on economic growth, with an emphasis on creating institutions for good governance, transparency, and rule of law. These provide the fertile conditions for investment and the diffusion of new technologies

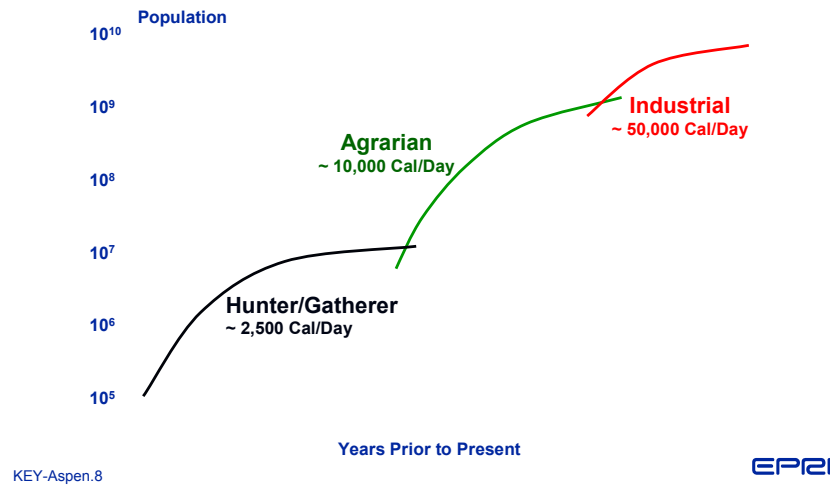
## I. Introduction

The pace of human civilization is measured and moved by our capacity to harness energy. Primitive hunter-gatherer societies seized about 2500 calories per person per day from the land—most of it eaten directly in vegetarian diets. Fire for cooking, heating and light added more primary calories to energy budgets. Domestic agriculture required still more primary energy—for humans and eventually animal engines to do the work. The surplus from agriculture freed people from the land and made urban life possible, and the innovations of dense living included new materials such as clay, bronze and eventually steel that required hot fires. As shown in Figure 1, each major pulse in the expansion of economic activity—and the organization of society—has required a quantum leap in primary energy. Energy and development have gone hand in hand. Under-development is both measured and caused by poor access to energy services. Our persistent problems of under-development will be hard to solve without, at the same time, advancing a vision for expansion of the world's energy system.

What should be the goals and milestones for the energy system? To what degree will the world's economies meet such targets on their own? Where must active efforts be concentrated, and what should firms, governments, R&D facilities and NGOs do to help? What policy instruments and institutions are likely to work best? This essay explores these questions and provides some answers.

We narrow the inquiry in two ways. First, we focus on energy consumption in the least developed societies, those with generally the lowest levels of energy consumption. We set aside issues associated with the high end—whether, for example, the post-industrial society will require the same quantum jump in primary energy (along with a similar jump in power quality) that earlier waves of economic growth have demanded (Figure 1). Those issues are important, as everyone who is running bigger wires to their homes and offices and to power-hungry computer server “farms” can attest. But such matters, and their implications for R&D agendas, are addressed elsewhere in the EPRI strategic roadmap. Second, we focus only on electric energy. Over the last century the advanced industrialized countries have electrified their economies such that about half the primary energy is connected to electrons before final use. Flexibility, ease of control, and cleanliness make electricity the energy carrier of choice.

## Cycles of Demographic Growth



**Figure 1.** Growth in energy consumption has occurred in pulses, with each major reorganization of society leading to (and caused by) a new pulse in our ability to harness energy. Each reorganization has also yielded 1-2 orders of magnitude greater world population. *Source: EPRI (1999), Yeager (2002).*

What should be the vision for electrifying the world? Our aim is to propose and defend some goals for global electrification. As we will see, this is not an easy task, so we approach it from several different angles. First, we review findings from “micro” studies on energy use, such as household energy surveys. Those studies allow us to suggest some targets, based on real household experience, for minimum acceptable levels of energy consumption. We conclude that section with the claim that a reasonable goal for *minimum* per-capita annual consumption of electric power is about 1000 kwh. Second, we examine “macro” patterns in the relationship between energy consumption and welfare. Those macro patterns suggest a strong and steady relationship between electric inputs and economic outputs; they also suggest that reasonable growth in the world economy over the next 50 years should lift average electric power consumption per capita to about 9000 kwh, or about four times current levels. Third, we examine the experience with policy instruments designed to promote electrification. That experience allows us to put some bounds on the cost of electrification, and it also suggests some key knowledge gaps that must be filled with active R&D and policy reform.



## II. Context: Who Electrifies and Why?

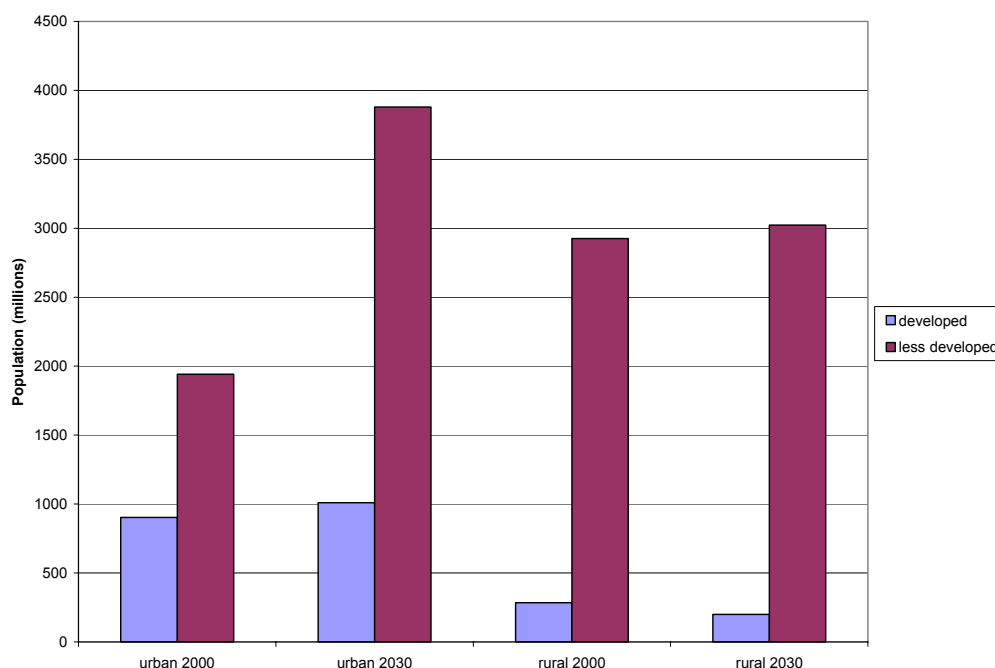
Before we outline and support a vision for global electrification some contextual information is required. What are the demographics of people that this vision is intended to serve? Why is provision of modern energy services—in particular, electricity—an important mission for the world and the industry?

### *Demographics of the Under-served*

First, how many are there? Earlier studies have suggested that perhaps 1.5 to 2 billion people have no “access” to modern commercial energy services. In the course of our inquiry we will suggest some numbers of our own, but it is critical to underscore several flaws with these numbers. These numbers are extremely soft and difficult to support. And their softness derives from a severe analytical flaw in the whole concept of “access.” The electric power system is not a Field of Dreams—neither the builders of energy supply and distribution systems nor the consumers behave as automatons, and the worldwide shift to using market forces in the electric power system make it increasingly important to look at the underlying economics—to look beyond access at the forces that explain behavior of suppliers and users. The goal of electrification is not just hooking houses to wires but also creating an economic and institutional environment where people can actually afford to acquire the energy that they need. By that measure, some have suggested that perhaps 3 billion (or more) people are under-served by electric power. But how far are they under-served, and can we suggest some concrete measures beyond the tautology that half the world’s population consumes electricity at rates below the world median? We will suggest some answers.

Second, where do the under-served live? Strategies for supplying these approximately 2 billion people vary with many factors, but there are two distinct approaches—depending on whether the under-served are in less dense rural areas or more compact urban agglomerations. Today, the vast majority of the 1.5 to 2 billion who are under-served live in rural areas where incomes are lower than in cities and, because the distances to the grid are longer, the cost per electric power connection is generally much higher. Not only do most of the under-served live in rural areas in developing countries, but most people living in those areas are under-served. As shown in Figure 2, today’s rural population in developing countries is about 2.8 billion people, while perhaps 1.7 billion live in urban areas. The rural population is expected to remain approximately stable over the next 3 decades; population growth in the developing countries will concentrate in cities as people move from the countryside. We do not have projections for urban and rural populations in 2050, but it is likely that the absolute numbers of rural people will be smaller in 2050 than today. We are mindful, however, that one of the great demographic uncertainties is the pace of this urban shift and whether and how policy makers should

slow or redirect urbanization. Urbanization in the more developed world stands at about 76%; in the less developed world it is only perhaps 40%, so there is enormous potential migration into urban areas in developing countries (HABITAT, 2001). The rate of migration may not be entirely independent of electrification; anecdotal evidence suggests that people served in rural areas are less prone to migrate to cities. Finally, it is worth underscoring that the problem of poor access to electric power has been nearly equated with the problem of rural energy, and we too will focus on rural areas. However, a small fraction of those who have no access to modern energy live in urban areas.



**Figure 2:** Current and future urban and rural populations. *Source: HABITAT (2001).*

### *Benefits of Electrification*

We do not seek, in this essay, to provide an elaborate description of why global electrification is vital. Other studies have explored the benefits of modern energy systems in detail (e.g., UNDP, 2001; WEC/FAO, 1999; UN DESA, 2001; EPRI, 1999; ESMAP, 2000). Broadly, the benefits are threefold. First, non-electric fuels are often associated with severe health effects. In the advanced industrialized countries most of the public debate about air pollution focuses on the outdoors, especially in urban areas. Viewed globally, however, by far the greatest human exposure to air pollution occurs indoors in rural areas—in part because nearly half the world’s population lives in rural areas and

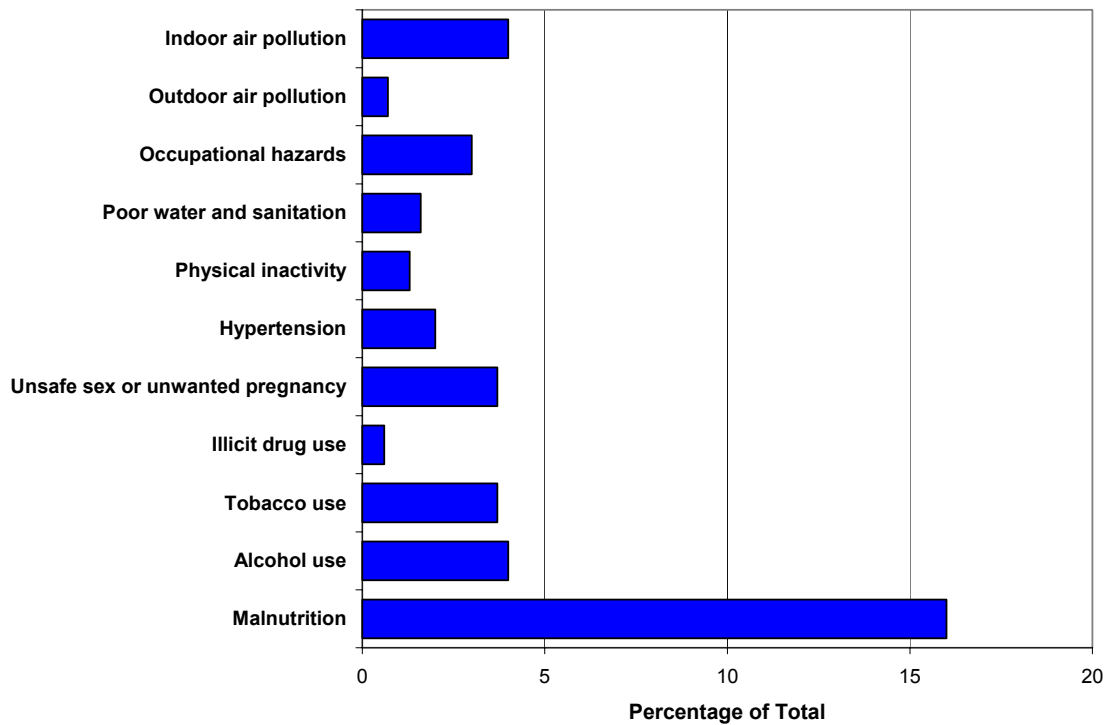
mainly because rural dwellers tend to be poor, and the poor satisfy their energy needs with highly polluting fuels. For example, Table 1 shows typical indoor exposures to particulate matter due to cook stoves. More efficient stoves can reduce those particulate concentrations sharply. Switching to cleaner fuels can allow further reductions. Switching to electricity can reduce this pollution source to zero. Figure 3 helps to put these exposures into perspective, underscoring that while indoor air pollution is one of the largest killers, malnutrition is much worse. For many, the biggest source of pollution is not an unwanted byproduct of activities such as cooking and heating but wholly self-inflicted with cigarettes.

Studies have documented average exposures and (in some places) peak exposures to major pollutants released during the burning of traditional fuels, but more work is needed to assess exposures on finer time resolution.<sup>2</sup> Particular attention is needed to the problem of particulate pollution—not just on absolute levels of particulates (measured as particles or mass of particles per unit volume) but especially on the types of particles associated with different fuels and combustion technologies, as new research on the health effects of particles shows that particle size is a major factor in determining health effects. Similarly, work is needed on the wider range of health and safety issues associated with fuels, such as burns and house fires from spilled kerosene, electrocution from faulting wiring (and attempts to bypass meters), and so on. Viewed from the perspective of maximizing social benefit, it is also important that active efforts to promote particular fuels and technologies be informed by studies that compare the costs and benefits from these programs with other social investments, such as efforts to discourage smoking—another major cause of particulate pollution.

|                        | Indoor Concentration of Pollutants<br>from a Typical Cook Stove*<br>(mg/m <sup>3</sup> ) | Safe Levels<br>(mg/m <sup>3</sup> ) |
|------------------------|--|-------------------------------------|
| <b>Carbon Monoxide</b> | <b>150</b>   | <b>10</b>                           |
| <b>Particles</b>       | <b>3.3</b>   | <b>0.1</b>                          |
| <b>Benzene</b>         | <b>0.8</b>   | <b>0.002</b>                        |
| <b>1,3-Butadiene</b>   | <b>0.15</b>  | <b>0.0003</b>                       |
| <b>Formaldehyde</b>    | <b>0.7</b>   | <b>0.1</b>                          |

**Table 1:** The negative health effects of cookstoves. \*A Typical cook stove burns 1 kg of wood per hour in 15 ACH 40 cubic meter kitchen. Safe levels are typical standards set to protect health. *Source: Smith et al. (2000) as summarized in UNDP (2000).*

<sup>2</sup> For an early review see Smith (1993); for a recent study that looks at peak exposure within households see Ezzati and Kammen (2001).

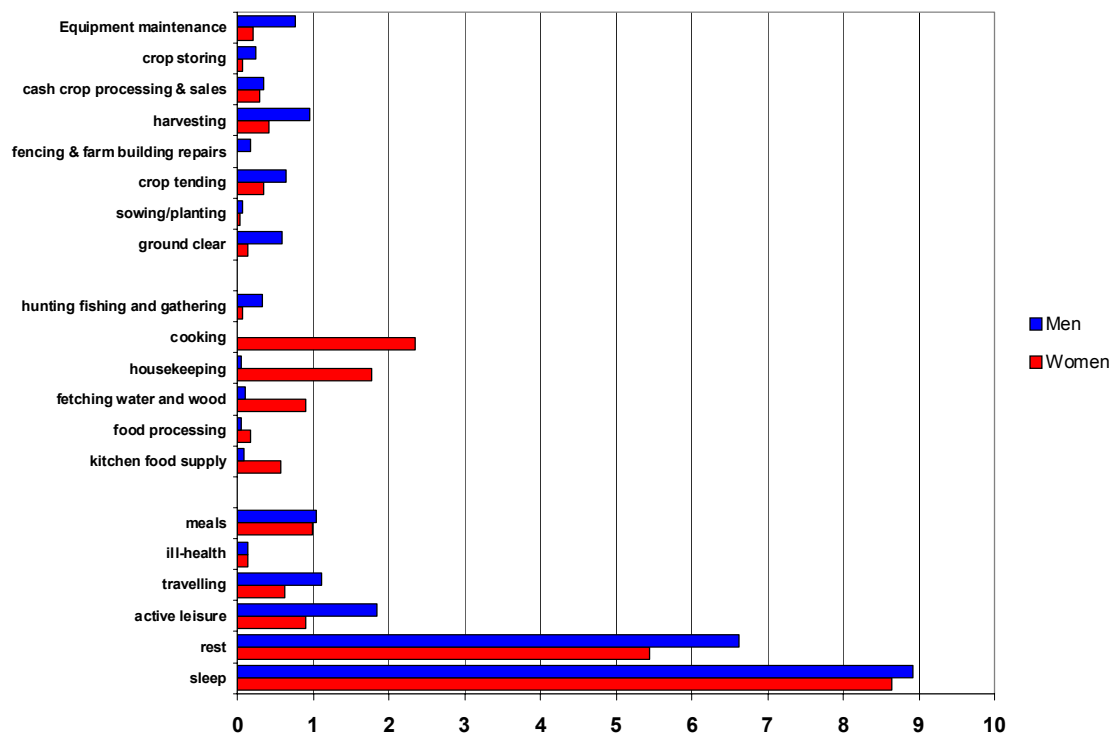


**Figure 3:** The global burden of disease from selected major risk factors, expressed in percentages of total worldwide DALYs.<sup>3</sup> *Source: Smith (2000) and Murray and Lopez (1996), as summarized in UNDP (2000).*

A second benefit is measured in time budgets. As shown in Figure 4 in low-income areas such as rural Ivory Coast much time is spent on collecting fuel and cooking, and most of that effort consumes the time budgets of women. Electrification can free that time, and more work is needed to explore how the free time is then spent. If the opportunity cost of those hours is zero then the time budget perspective would suggest that liberating the time of women will yield no economic benefit. However, much anecdotal evidence suggests that women are the key players in rural development; some anecdotal studies have traced a rising role for women in rural economies to the time freed by substituting commercial energy for female labor—such as in milling, where programs to transfer mechanical milling machines have freed women for other activities (UNDP, 2001; Karlsson, ed., 2001). More generally, a large number of studies demonstrate the strong

<sup>3</sup> DALYs, or Disability-Adjusted Life Years, is the sum of years of life lost due to premature death (calculated in the conventional manner), and years of life lived with a disability, weighted by the severity of the disability. A DALYs number is thus an estimate of world or regional loss of productive life years. Definition source: <http://devdata.worldbank.org/hnpstats/BOPNotes.htm>.

link between efforts to build human capital in women—such as education—and sundry benefits such as lower population growth and more stable families.



**Figure 4:** Time allocation for various activities in the Ivory Coast (hours/day). *Data provided by Dr. James Levine, co-author of “The Work Burden of Women,” Science 2001 October 26; 294:812.*

A third benefit, tied to the first two, is economic growth. Electricity can contribute to economic growth not only by allowing a healthier population and by liberating hours from dangerous and long tasks, but electricity also allows more productive industry—not only at the lowest levels of the economy but throughout the economic system. As already implied, at very low income levels we do not know exactly how electricity and modern energy services fit into and catalyze sustainable economic growth—it may be through time budgets generally or through the time budgets of women, and it clearly is affected by institutions that allow societies to pool their resources to purchase and manage energy services (e.g., a milling machine or a micro-grid).<sup>4</sup> Indeed, there is a close correlation between economic growth in rural poor areas and consumption of commercial energy, including electricity—but the direction of the causality has been difficult to unravel. Similarly, electricity is a vital input into modern economies and is essential to economic

<sup>4</sup> The institutional context is particularly important, and we return to that issue later. For an overview of the key economic issues see especially Hoff et al., eds (1993).

growth at high-income levels as well, although the exact causal links are difficult to discern at the macro level. We will present some data later in this essay that quantifies the links between electric inputs and economic outputs.

Studies have cited many other related benefits as well. Among them is the role of commercial energy in managing the problems of urbanization. Successful rural energy programs might lighten the pressure to leave the countryside for cities. A proper assessment of that hypothesis, however, requires an assessment of the range of other costs and benefits of rural and urban life. Moreover, because of the economies of scale even in modest energy systems favor, often rural energy programs are concentrated in some areas while other rural locations remain unserved, leading to rural-rural migration. A village with lighting might become a magnet for local commerce able to operate indoors and after sunlit hours, drawing commercial activities away from surrounding villages but deterring (or deferring) migration to cities. Assessing the magnitude and allocation of costs and benefits of such effects is a complicated and difficult task. Under some conditions, successful electrification might reduce pressure on forests due to gathering of fuelwood, although several studies suggest that the problem of deforestation caused by biomass consumption has been much over-stated.<sup>5</sup> Some energy systems may offer special opportunities for employment, which contributes to the local economy and is an additional reason why successful energy strategies could slow pressures on urbanization—such links to employment have been made, especially, for biomass and other renewable energy options (e.g., Kammen et al., 2001).

### **III. Micro-level Studies**

What do the data at the level of individuals and households reveal about energy consumption patterns among those who have no access to modern energy services? The World Energy Council and Food and Agriculture Organization recently conducted a comprehensive survey of rural energy use, which reveals some basic patterns (WEC/FAO, 1999). First, nearly all energy use in the poorest rural areas is consumed within households, averaging more than 85% of the total energy budget. The little energy that is used outside households is deployed mainly in agriculture (which is often, itself, a small-scale activity organized by household rather than a distinct economic sphere), principally for pumping water. The other prime movers in agriculture are people and animals. One study by FAO using data from 1980 suggested that the agricultural sector in developing countries was powered 60% with energy from humans; 30% from animals; and the small

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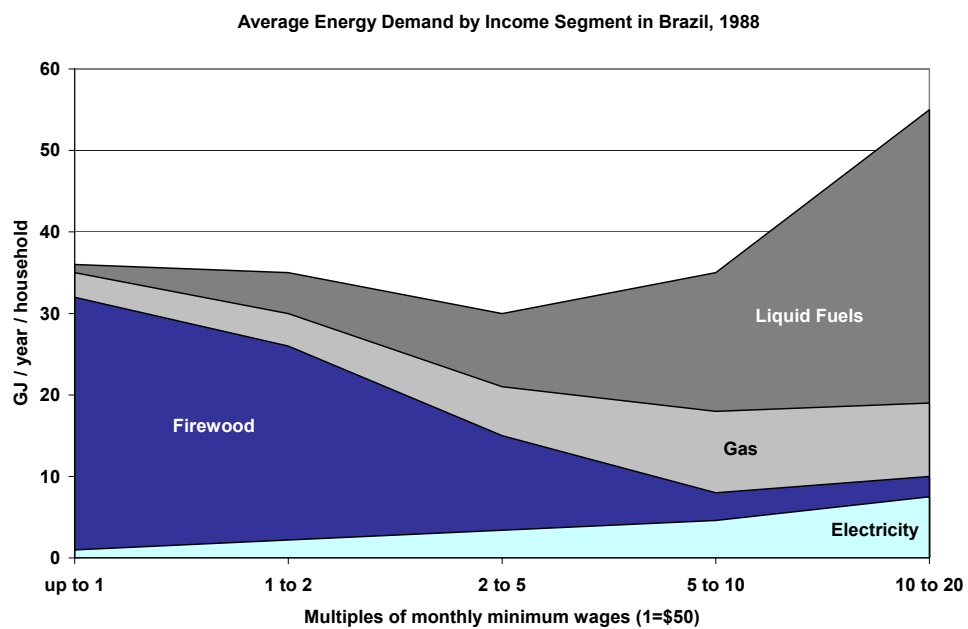
<sup>5</sup> The over-statement stems from the fact that much fuelwood is gathered from trees and hedges that are grown sustainably and, often, are in patches of woods or windbreaks that do not qualify as “forest” under conventional definitions. For a recent review see WEC/FAO (1999) and for a particular case study on energy and forestry policies see Foley et al. (1997).

amount of rest mechanical, usually diesel or electric water pumps (Hicks, 1997, cited in WEC/FAO, 1999).

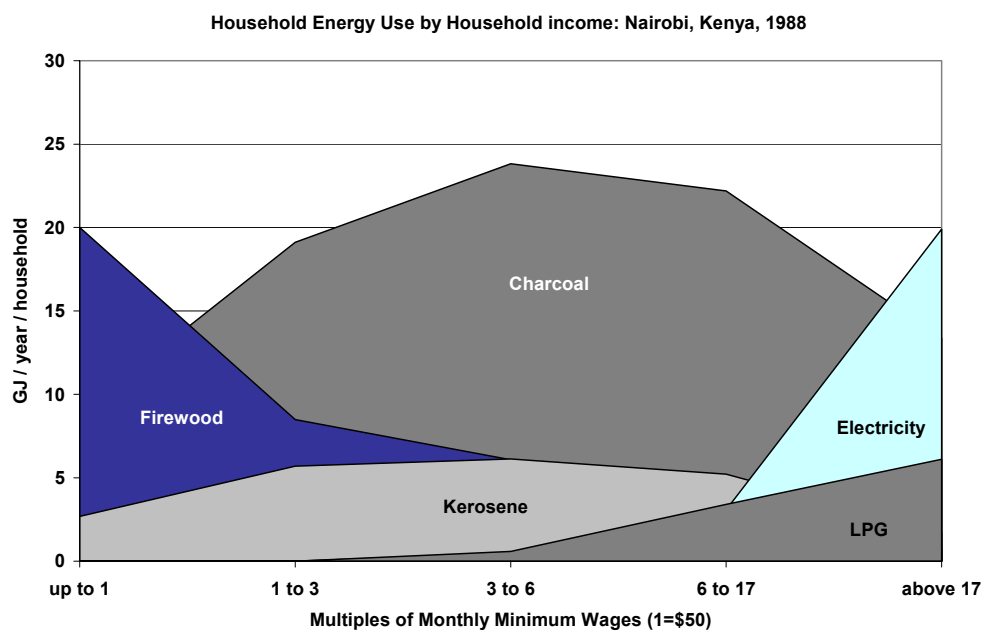
Second, of the household energy budget, nearly all goes to cooking. Since most of the rural poor live in areas that are relatively warm, little energy is needed for heating; however, where temperatures are lower, a substantial fraction of fuel is burned for heating as well. In Chile, for example, rural household surveys suggest that half of useful energy goes to space heating and most of the rest for cooking, whereas in Africa and southern India almost no energy is used for heating and more than 90% of the household energy budget is devoted to cooking (WEC/FAO, 1999, section 2.3).

These basic patterns—that energy use in poor rural economies is concentrated in households and that cooking (and, in some areas, heating) is the dominant use for primary energy—are pretty robust. As expected, a close look at household energy surveys reveals many variations, such as variations in fuels. In Brazil, for example, firewood is the dominant fuel at low-income levels (Figure 5, Panel A) and is replaced by liquid fuels such as sugar-based alcohol fuel as incomes rise. In contrast, in Kenya (Figure 5, Panel B), income growth replaces firewood with charcoal and a lesser amount of kerosene; at high incomes, charcoal (historically a fuel of choice in Kenya) remains a substantial part of energy budgets, and LPG and especially electricity dominate the rest of the household energy budget (O’Keefe et al., 1984 cited in Leach, 1992). In communities where there is no access to modern energy services, traditional fuels dominate household budgets even at high income levels (Leach, 1992). Conversely, where such modern energy services are available, even at extremely low income levels a small (but significant) fraction of household energy budgets is often supplied by kerosene or electricity—both of them modern, commercially-traded fuels.

**Figure 5 (Panel A)**



**Figure 5 (Panel B)**



**Figure 5:** Fuel use in Brazil (panel A) and Kenya (panel B) as a function of income (1988 US\$). *Source, Panel A: De Almeida and de Oliveria (1995), as summarized in UNDP (2000); Panel B: adjusted from O'Keefe et al. (1984), as adjusted in Leach (1992).*



The first joules of commercial energy are typically devoted to lighting; where electricity is available, often the contest is between kerosene and electricity to supply the service of lighting.<sup>6</sup> Some studies have compared the tradeoffs between kerosene and electricity in markets where both are available and find that the quality and efficiency of kerosene lighting are so low that each joule of useful electric power is 2 to 6 times more valuable than a joule of kerosene. This is one reason why people in rural areas have been willing to pay large premiums for electric power—not only is electricity able to meet some needs, such as television, that other carriers are unable to serve, but it also beats the competition for the core service of lighting.

Surveys of household energy budgets suggest that there is a hierarchy or pyramid of *energy* services, with cooking and heating at the base, followed by lighting and entertainment (radio and TV) and then appliances such as electric irons and refrigeration. Meals and warmth are essential, followed by sports scores and *Baywatch*; illumination offers the ability to wrest control over the day's pace from the solar cycle; pressed shirts and long-term food storage follow later in the chain of basic needs. That is the hierarchy for *all* energy services. The hierarchy for *electric* services is somewhat different; in the poorest households the base of the energy pyramid is usually supplied by non-electric services, and the first few kilowatt-hours of electric service are devoted to tasks much higher in the pyramid.<sup>7</sup>

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<sup>6</sup> There are many exceptions to general statements about household energy budgets. I underscore two here. First, in areas that favor coal and charcoal, those fuels are typically traded commercially and typically used for heating and cooking. Thus they are the first “commercial” fuels to enter the energy budget. (Some studies thus examine in the shift in fuels in terms of “traditional” and “non-traditional,” but it is equally difficult to draw a fine line between those two categories.) A second exception to the general rule here applies to areas where LPG and kerosene are amply available (and often subsidized) for cooking fuels; in those settings households often move quickly to LPG or kerosene cooking. Because the caloric requirements for cooking far exceed that of other household activities (except in cool areas, where heating is also important), in such settings the effects of cooking dominate the household energy budget and it is not literally true that the “first joules of commercial energy are typically devoted to lighting.” In those settings, households also allocate kerosene and LPG (and electricity, if they can get it) for lighting, but the energy content is much less than the cooking service.

<sup>7</sup> Many authors refer to an energy “ladder,” with the first rungs as firewood and other non-commercial traditional fuels, followed by LPG and kerosene and then electricity. This paper avoids that terminology as it is misleading in at least two ways. First, there is no single progression of rungs, as illustrated in the earlier comparison between Brazil and Kenya. Second, real household energy budgets do not progress in lumpy step-like fashion but, rather, are more like a vector of energy services. Even very poor households, where they have access, take a few small steps on the high “rungs” of electricity while the bulk of their energy is supplied at lower rungs. The persistence of this ladder concept may owe to the fact that, despite claims to the contrary, household energy budgets are typically measured in terms of primary energy rather than useful energy, which overstates the low (extremely inefficient) rungs on the ladder and the lumpiness of the progression from one fuel to another. The value derived from purchasing very small energy units of commercial fuels, as revealed by a household's willingness to pay, is much larger than the high volumes of primary energy devoted to basic services like cooking and heating.

It is illustrative to compare this experience with the early penetration of electricity into the U.S.<sup>8</sup> Lighting was the first and always the most important use. Gas lighting, for those rich enough to have gas piped through their homes, provided poor illumination, it flickered, gave off emissions and unwanted heat, and worst of all, was dangerous. No one was willing to leave a child alone in a room with gas lamps. Electric lighting allowed the family to disperse in the household without fear, turn their back momentarily on the kids, and to stay up past 9:00pm.

In the 1880s and 1890s, entertainment in the broadest sense was an important use of electricity. This was before broadcast entertainment, but social establishments (hotels, meeting halls, theatres, even high end bars) used electric lighting to bring in the curious who stood about gawking at light without heat, combustion, smoke or flicker. It didn't make any sense and was miraculous enough to become the entertainment itself. All the Great World Fairs at that time were carnival displays of lighting. Edison, ever the PR man, had a parade of guys with lightbulbs on their heads walking down Wall Street, and nobody laughed.

Next on the hierarchy were appliances—the most important being the electric iron, and by 1910 or thereabouts the vacuum cleaner. People said they would rather have a vacuum cleaner than indoor plumbing. The ability to clean the rugs every week rather than beating them outside twice a year—think of moving all that heavy Victorian furniture about—was seized upon. (Once the house was cleaner, and hot water became available, “cleanliness next to Godliness” took on a whole new meaning. People bathed more, washed their clothes more often, and of course, needed more clothes to wear and wash. )

Electrification was the rich man's conspicuous luxury and the poor man's entertainment until about 1910, when universal electrification in the US took off (farms repeated the cycle in the 1930s). Appliances all diffused into service over 20-30 year periods, except for radio. After the Great War it was discovered that radio was useful for than just military traffic, and the penetration curve for radio sets was nearly vertical.

All in all, peoples needs and preferences for electricity have been remarkable similar: lighting first, entertainment second, appliances third.

### *Minimum Needs*

It is not obvious, from the household energy data, what should be a defensible goal for minimum household consumption. One way to frame such a target is to focus on usable energy for three purposes: cooking, heating, and other services. For cooking, we take our cue from the government of India, which uses a goal of about 1 GJ of useful energy per capita per year for cooking (WEC/FAO, 1999). That goal is framed in terms of

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<sup>8</sup> For an overview see Nye (1991) and Hughes (1989).

useful energy, not electricity—indeed, most Indian cooking in rural areas is not electric, and government programs to diffuse clean cooking fuels usually focus on LPG or other commercial fuels, not electricity. Obviously, appropriate goals will vary, not least because diets vary and some foods are inedible unless cooked. 1 GJ is equal to 277 KWH, although comparisons between the fuels used in the Indian context and electric stoves requires, of course, accounting for losses in converting the primary fuel to usable heat.

These numbers appear to be much lower than actual consumption of useful energy in other regions. Guzman's (1982) study of rural energy use in Mexico suggests that end-use of energy for cooking is about 8 to 10 GJ per person per year for the lowest income levels. The household data shown earlier, in Figure 5, also support values much higher than 1GJ per person per year, but when setting targets for electric power it is essential to keep in mind that electric appliances are much more efficient than traditional cookers that they replace—typically by one order of magnitude when measured as the primary energy content required to cook a set meal. Those efficiency improvements explain why the Guzman (1982) study in Mexico, among others, reveals a drop in total end use of energy as incomes rise—apparently because wealthier households are able to afford new energy equipment that is easier to use, less polluting, and also has the benefit of higher efficiency. Typically, that drop is soon reversed, such as shown in Figure 5 (Panel B) because the greater efficiency of new equipment (usually new cookers) is offset by greater use of energy for heating water and for space heating and other energy services.

For heating, it is impossible to set a single target since the quantity of useful energy will vary with climate.

For all the other uses of energy we must make some even more heroic assumptions. We focus on electricity supplying three basic functions: lighting, entertainment and household appliances. A bare bones electricity budget might include 6 hours per day with 50W of lighting, or about 10 KWH per month, with similar levels of consumption for the other two functions—leading to a budget of about 30 KWH/month. For comparison, the South African political parties are presently in the midst of a debate over the minimum quantity of electricity that should be supplied to all houses that have been electrified. In Cape Town the current, politically selected value is about 25 KWH/household/month (approximately the same as our simple budget above), and the political debate in South Africa is now focusing on a value of about 50 KWH/household/month. But even a budget of this level is not adequate to supply a level of refrigeration for even modest in-home food storage. Including that service as well, the minimum target for these all the non-cooking and non-heating functions may be about 100 KWH/household/month, which is about 200 KWH/person/year. These values are consistent with the average electric power consumption in South Africa today (see Table 2).

|                                    | 1994   | 1995   | 1996   | 1997   | 1998   | 1999   |
|------------------------------------|--------|--------|--------|--------|--------|--------|
| Connections                        | 435756 | 478767 | 453995 | 499311 | 427426 | 443290 |
| Capital cost, R millions           | 1482   | 1412   | 1473   | 1176   | 1235   | 1186   |
| Capital cost per connection, R     | 3179   | 3370   | 3417   | 3159   | 3008   | 2975   |
| Operating cost/connection, R/month | 26     | 24     | 23     | 26     | 19     | 19     |
| Energy/connection, kWh/month       | 80     | 78     | 86     | 99     | 107    | 95     |
| Income/connection, R/month         |        |        | 19     | 24     | 27     | 28     |
| c/kWh average                      |        |        | 22.1   | 24.2   | 25.2   | 29.5   |

**Table 2:** Cost of connection, operating cost, and income from South African electrification program. *Data from Eskom reported in Magubane (2001), cited in Lloyd (2001).*

### *A Target for 2050*

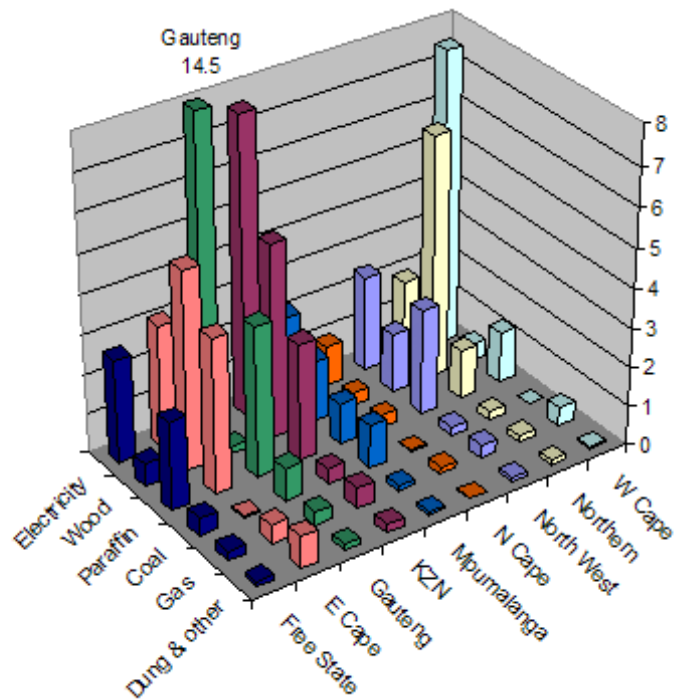
Our task in this essay is not to develop a defensible goal for minimum electric power *today* but, rather, 30 to 50 years in the future. To do that we must make four more sets of assumptions. First, we must estimate changes in energy services. What new functions, beyond those listed above, might become viewed as essential minimum services in the future? No doubt the list of basic appliances will probably grow, although whether these will be viewed as essential minimums is hard to estimate. The list of choices is not much different from those available 50 years ago in the advanced industrialized countries; beyond radio, television, irons, and refrigeration it is arguable whether there are more choices. The best candidate, however, is in-home computing, which might add another 50 KWH/person/year (that is, 2 hours of computing, two out of every three days, with power draw of 100W/hour). That would suggest that core electric services that are difficult or impossible to supply with non-electric fuels or energy carriers would be about 250 KWH/person/year.

Second, we must make assumptions about changes in efficiency, and the potential for changes in efficiency over several decades is substantial. At one extreme, an ultra-efficient energy system could dramatically reduce the need for electric supply in rural areas, and by reducing the total quantity of required electric service it may be possible to meet basic needs with a wider range of supply options—including decentralized renewable power supplies, many of which do not offer the power density of centralized grid-based electric systems. For example, Goldemberg et al. (1985) have already pointed out that energy services are supplied extremely inefficiently in rural areas—so much so that all basic energy services could be delivered, they argue, with only 1 KWH/person/year of useful energy (electric and non-electric combined).

Third, to set the minimum we must also look outside households, especially at agriculture. How much energy will be needed for agriculture—for mechanical working of the land, for fertilizers, for pumping water, and for milling of final products? We already know that water pumping probably increases our minimum per-capita values by a few KWH/person/year. Furthermore, actual experience with milling machines in rural areas

suggests that communities place a very high priority on acquiring such equipment. For example, the United Nations Development Programme has had success in diffusing its “multi function platform” in Mali, where women have organized cooperatives to buy and maintain the machines, paid for with small fees charged to users of the milling equipment (UNDP, 2001). To date, nearly all such experience is with diesel powered machines, but in communities where electricity is available such machines could also be run with electrons. We must look outside the household, also, to energy uses for small-scale industry, although it is harder to say how much small-scale industry should be included when setting a goal for the minimum acceptable electric supply—the minimum, presumably, is a matter for rural areas. We will return to this issue, which in essence is the question of economic growth and energy consumption, in the next section.

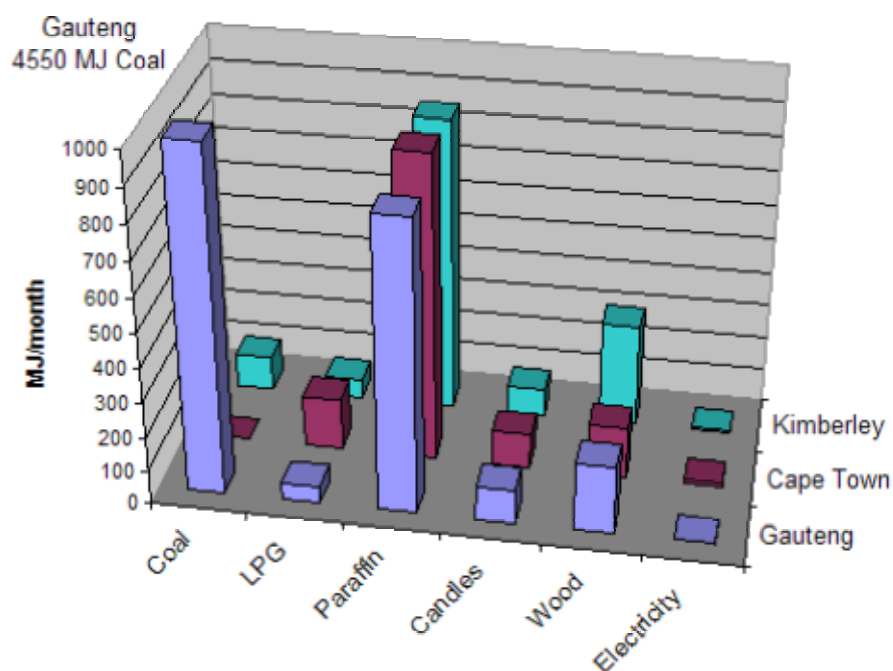
Fourth, we must make assumptions about how much of the energy budget is supplied via electrons and how much is delivered in other ways. This is the single most important determinant because cooking and heating are so dominant—they are the base of the pyramid. In most rural areas these energy services are supplied by wood (direct or charcoal), kerosene or coal—electricity is rarely used. Because this is so important we dwell on the possibilities for a moment, using the experience in South Africa—the country with the most successful electrification program—as a guide. The 1996 census in South Africa was a comprehensive attempt to take the pulse of energy choices in the country, and as shown in Figure 6 the data suggest that electricity can be the fuel of choice for cooking. The data do not reveal the quantity of fuel consumed for cooking or the distribution by income, and they may be plagued by problems caused by self-reporting. Electricity is a luxury fuel and there may be peer pressures to report electric cooking when, in reality, coal and wood are the household prime movers. Nonetheless, the census data do suggest that in a country with active electric efforts a large fraction of cooking needs could be supplied by electric power.



**Figure 6.:** Fuel choice for cooking (hundreds of thousands of households). Note: Gauteng province is shortened. *Data from the 1996 South African census, compiled and presented in Lloyd (2001).*

The South African experience also allows us to probe further—to see the role of electricity at very low income levels. Figure 7 shows results from an earlier study in South Africa for “planned shacks” in three urban areas. This study is especially useful for our purposes because it probes energy consumption at the lowest income levels—planned shacks typically consist of only minor improvements (sheet metal and plastic for walls and roof). They are generally built in close proximity to similar dwellings in areas that have basic utility services, including electric power, and thus the experience in these shacks allows us to measure the contest between electricity and other energy services. Whereas Figure 6 showed self-reported data on fuel choice, the study on planned shacks shows the quantity of fuel consumed in the lowest income levels—except in Gauteng, the wealthiest region, which includes Johannesburg and Pretoria—where coal is abundant and cheap and thus used at very high levels, paraffin is the dominant fuel. Table 3 reports basic information on these fuels, including estimated costs, and suggests that the dominance of kerosene may be irrational. Kerosene has higher costs per unit energy; wick-style kerosene cookers cause large amounts of pollution (particulates and CO) relative to electricity; and perhaps 85,000 people die every year in household fires touched off by kerosene. The least efficient cookers have lowest capital costs and may explain some of the dominance, but a comprehensive review of fuels by Lloyd (2001) suggests that the main explanation for king kerosene is conservatism in households. People are loathe to deviate from the

familiar. On its own merits, electricity has made major inroads into household energy budgets—even for cooking—and efforts to provide fuller information about electric benefits would make further diffusion possible



**Figure 7.:** Energy budgets for “planned shacks” in three urban regions. Except in Gauteng, paraffin (kerosene) is the dominant energy supplier—mainly for cooking and also for lighting. Most paraffin is burned in wick-style stoves. The data for Gauteng are cut off to allow easy display. Table 2 shows estimates for the energy content, cost and average total household energy cost. *Data compiled in 1994 by EDRC at the University of Capetown and reproduced in Lloyd (2001).*

|              | Average use | Cost  | Unit  | Unit energy | Cost per MJ | Cost per month |
|--------------|-------------|-------|-------|-------------|-------------|----------------|
|              | MJ          | R.c   | per   | MJ          | R.c         | R.c            |
| Electricity  | 10          | 0.30  | kWh   | 3.6         | 0.08        | 0.83           |
| Paraffin     | 865         | 4.00  | litre | 34          | 0.12        | 101.76         |
| Wood         | 220         | 0.50  | kg    | 18          | 0.03        | 6.11           |
| Candles      | 95          | 10.00 | kg    | 40          | 0.25        | 23.75          |
| LPG          | 85          | 8.00  | kg    | 40          | 0.20        | 17.00          |
| Coal         | 135         | 0.40  | t     | 25          | 0.02        | 2.16           |
| <b>Total</b> | <b>1410</b> |       |       |             |             | <b>151.62</b>  |

**Table 3.:** Estimated average cost for energy services in the “planned shacks” shown in figure 3. *Source: Lloyd (2001).*

The study of planned shacks shown in Figure 7 also provides another data point for total fuel consumption at low income levels. Setting aside the coal-distorted data from Gauteng, average total fuel consumption is about 1.2 GJ/household/month, which is probably equivalent to about 2-3 GJ/person/year. These figures are much lower than the 10 to 12 GJ/person/year suggested in the Mexican surveys; the low level is even more striking when considering that even at very low income levels South African energy budgets include large amounts of space heating—typically about half of the budget goes to heating and about half for cooking, with both those fractions declining as incomes rise and other energy services enter the budget. There are two reasons why we should put greater weight on the lower figure for total minimum household energy consumption as a guide for our exercise—for setting goals for the next few decades. First, the energy budgets in the South African planned shacks are dominated by relatively efficient fuels (kerosene, coal, electricity) and thus these energy surveys are less likely to be plagued by problems in estimating primary versus useful energy. Typically energy surveys are reported in terms of “useful” energy, but the numbers vary so widely that it is likely that there are serious methodological problems in dealing with fuels that are converted to useful form (e.g., cooking heat inside a pot) at very low efficiency levels, and those errors probably lead to over-estimation of the actual consumption of useful energy. Second, energy budgets that include more efficient fuels reveal some of the potential for improving end-use efficiency; when looking to 2030 or 2050, even when setting a minimum goal for energy consumption, we must envision that primary energy consumption in the least wealthy households is likely to decline even as useful energy rises. Indeed, most cross-section and time series energy budgets for low-income households reveal that pattern.

What are the implications of all this for targets? It suggests that the absolute minimum target for electrification is about 250 KWH/person/year. But that target is defensible *only* if we assume that electricity is not used for cooking and heating, and that assumption is probably difficult to support. The alternatives to electricity are all marked with problems—traditional stoves that burn biomass (e.g., wood or charcoal) are highly inefficient, wood-based fuels sometimes place severe demands on local ecosystems, coal and wood burned in open stoves causes extremely high levels of particulate pollution, kerosene is inefficient and polluting in inexpensive wick stoves and not cost-effective when compared with electricity (where electricity is available) in more elaborate stoves. Similar arguments can be made against the alternative fuels for heating. Either we need a plan for solving the problem of inefficient and dirty cooking with fuels and technologies other than electricity, or we need a target that would include a large role for electric cooking—although, to date, practically none of the rural electrification programs has targeted cooking, and households themselves do not choose to spend scarce resources on the high capital cost of electric cookers and the high operating costs of supplying them



with power.<sup>9</sup> Usually, rural energy programs seek to upgrade traditional cookers with more efficient technologies, create incentives to shift to kerosene or LPG or cooking, or ignore cooking altogether.

The potential for electric cooking is one of the key unknowns in our target setting. Making some provision for cooking would lift the target to somewhere around 1000 KWH/person/year. It is unlikely to be less than 500 KWH/person/year, unless the future defies the past and future societies envision a range of energy services as essential to modern life yet consume less energy than today. The actual value could be substantially larger, especially in all-electric households in cool climates. (We have not considered air conditioning as essential.) Future societies may also raise this value as they take into account the electric requirements for productive industry. Nonetheless, we will use this number—1000 KWH/person/capita—to illustrate the enormity of the task in electrifying the world, but we are mindful that the real number is soft and may be much lower with solutions to the cooking and heating problem—not to mention more efficient end use technologies.

To put this number into context, it is about one half the current level of average per-capita electric power consumption in the world. Data on within-country distribution of electric power consumption are not available. However, based on country averages we can estimate that around 3.7 billion people today live in countries where the average per-capita consumption of electric power is below the 1000 KWH per capita. Closing this deficit alone would require about 1950 TWH of electric power supply. Over the next 50 years we are likely to see perhaps another 3 billion people on Earth in the areas that, today, are already in electric deficit; net growth in the world population is likely to be less than 3 billion, but that net reflects some shrinking of the population in the advanced industrialized world even as the developing countries grow.<sup>10</sup> Serving those three billion will require another 3000 TWH of supply. For illustration,

Table 4 compares the average power consumption today in several selected developing countries with this 1000 kwh/person target. In the countries where the average level is in deficit the table also shows the total deficit and the number of large scale power plants that would be needed to bridge the gap. If these deficits were filled with grid-based power using large scale (1000 MW) plants operating at about 2500 hours per year then about 2000 new plants will be needed over the next 50 years *just to supply the minimum*

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<sup>9</sup> In South Africa, illustrated above, households in the lowest income level do not use electrons for cooking; the high use of electricity for some provinces shown in Figure 6 reflects that those populations are large and the wealthiest in South Africa. As shown in Figure 7, very low income “planned shacks” do not select electricity.

<sup>10</sup> These population assumptions are consistent with all of the families of scenarios for population that are used in the IPCC Special Report on Emissions Scenarios (Nakicenovic et al., 2000), except for the A2 family which assumes higher population (11.3 billion in 2050). The roadmap scenario from EPRI (1999) assumed a population of 10 billion in 2050.

target for electric power.<sup>11</sup> At a capital cost of \$1000/KW the total investment requirements (non-discounted) would be about \$2 trillion.<sup>12</sup> If these plants are built steadily over the next five decades then the annual cost would be about \$40 billion, which is nearly the level of all official development assistance for all purposes and about one-third of all foreign direct investment. Clearly this program will not occur automatically; it will require an investment strategy that relies mainly on private investment, and it will probably require a strategy that seeks to tap local investors as much more than private foreign investment.

| Country      | Electric Power consumption (kwh/capita, 1999) | Deficit (kwh/capita) | Total Deficit (TWh) | Deficit Power Plants (#1000MW plants @ 2500 hrs/year) |
|--------------|---|----------------------|---------------------|---|
| Brazil       | 1811  | no deficit           | no deficit          | no deficit  |
| China        | 758   | 242                  | 304                 | 121   |
| India        | 379   | 621                  | 619                 | 248   |
| Indonesia    | 345   | 655                  | 136                 | 54  |
| Malaysia     | 2474  | no deficit           | no deficit          | no deficit  |
| Mexico       | 1570  | no deficit           | no deficit          | no deficit  |
| Nepal        | 47  | 953                  | 21                  | 9   |
| Pakistan     | 321   | 679                  | 91                  | 37  |
| South Africa | 3776  | no deficit           | no deficit          | no deficit  |

**Table 4:** Electric Power Consumption and Deficits for selected major developing countries. “Deficit” values are computed simply by comparing average per-capita consumption today with the target of 1000 KWH/capita suggested in this essay. Note that the deficit calculation is not based on within-country estimates of inequality in power consumption. In highly unequal countries the number of people with power deficits, and the amount of the total deficit, is likely to be larger than implied in these simple calculations because income (and presumable power) inequalities are highly skewed, with few at the top and large numbers at the bottom. Also, note that the data shown here are per-capita and include both household and non-household (e.g., industrial) electricity uses; at low income levels most energy is consumed in households, and that generalization usually applies to electricity as well. *Data source: World Bank Development Indicators (2002).*

<sup>11</sup> 2500 hours per plant, although low by conventional measures for central power stations, may be very high as the actual experience with rural electrification programs suggests that the new load has high peaks associated with lighting and meals. Better storage technologies, end-use load leveling (e.g., water heaters), and pricing mechanisms for peak power pricing could play a dramatic role in reducing the capital cost associated with new generating and transmission capacity for these new loads.

<sup>12</sup> Such calculations are a bit fanciful because they ignore the technological improvements (which should reduce the cost of supply) and also do not account for the special infrastructure needs for serving rural populations (which should raise the cost of supply, unless low-cost non-grid technologies are deployed). The calculation is only intended to offer an order of magnitude for the undiscounted cost.

## IV. Macro-level Data

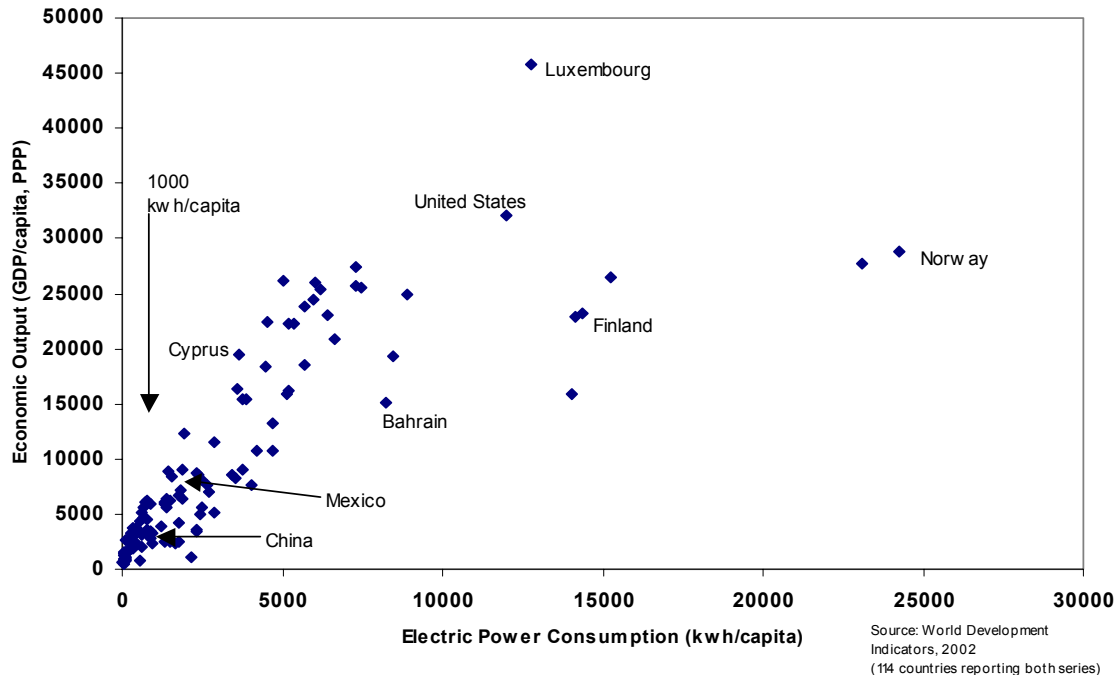
The data at the level of individual households suggest that a goal of about 1000 KWH/person/year. What can we learn from the macro level data—compiled at the level of provinces and countries? Do the data suggest targets for minimum levels of consumption or goals for the average consumption? After all, a strategy for electrifying the world should include not only electrification of the poorest but also a strategy for lifting all boats.

There are at least three ways to look at macro scale data: global cross-section, within country cross-section, and time series. None of these approaches is very helpful in identifying goals for *minimum* acceptable amounts of electric power consumption, but all of them reveal some basic patterns in the relationship between electric power consumption and economic output.

### *Global Cross-section*

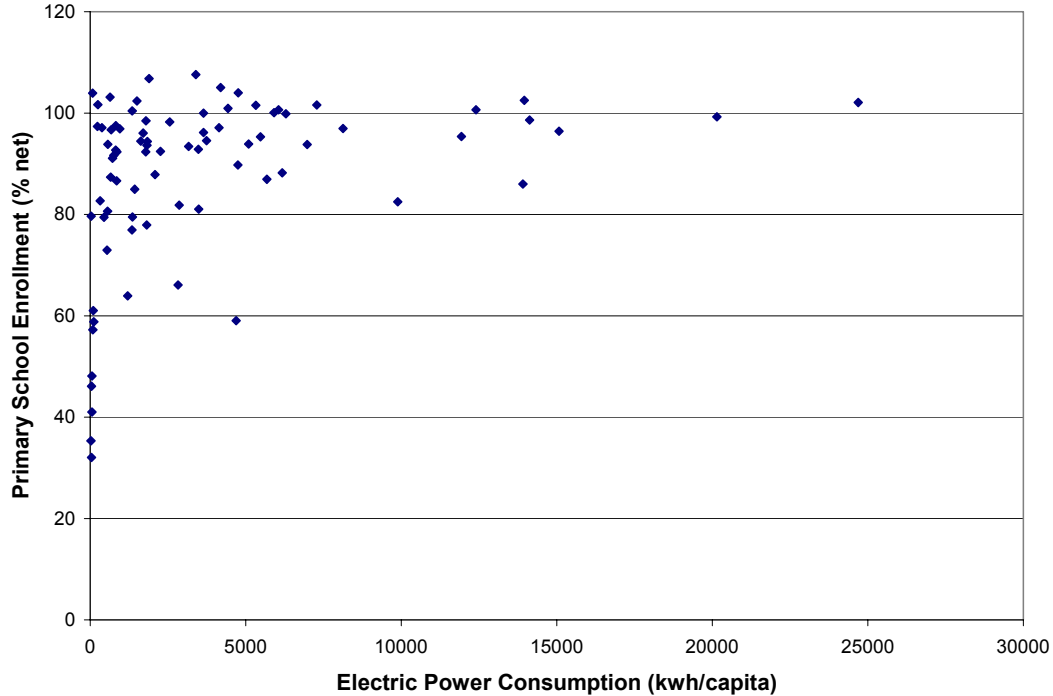
Global data, as shown in Figure 8, do not reveal any inflection point that could reveal a minimum acceptable amount of electric power consumption. Aside from outliers such as Finland, which input large quantities of electricity for relatively modest economic output (due mainly to highly energy intensive metal processing industries) there is a strong and seemingly steady relationship between electric power consumption and economic growth, with an exchange ratio of about \$3 per kwh. Interestingly the countries with the highest ratios of economic output to electric inputs are all in the developing world—such as Haiti (36 \$/KWH), Sudan (34 \$/KWH), and Nepal (27 \$/KWH). Some of these high values may be attributed to the method for calculating PPP exchange rates, which in effect lifts the incomes of poor countries because price levels for basic goods tend to be much lower in those nations. But mostly these values reflect the large potential for catchup economic growth in these nations and that the first few kilowatt hours of electric power supplied to an economy are enormously productive.

## Consumption of Electric Power and Economic Output, 1999



**Figure 8.** Cross-section of average national electric power consumption, 1999. Economic output data are compared using PPP exchange rates, rather than market rates. *Data source: World Bank Development Indicators (2002).*

The data that we present here underscores the critical role of electricity in modern economies and reveals strong relationships between electric power consumption and economic output. However, it is important to underscore that electricity inputs do not automatically lead to economic development. Other factors, such as investment in education, are largely unrelated to electric power, as shown for example in Figure 9. A winning strategy for economic development requires a broad base of investments; electricity is necessary but not, by itself, sufficient.



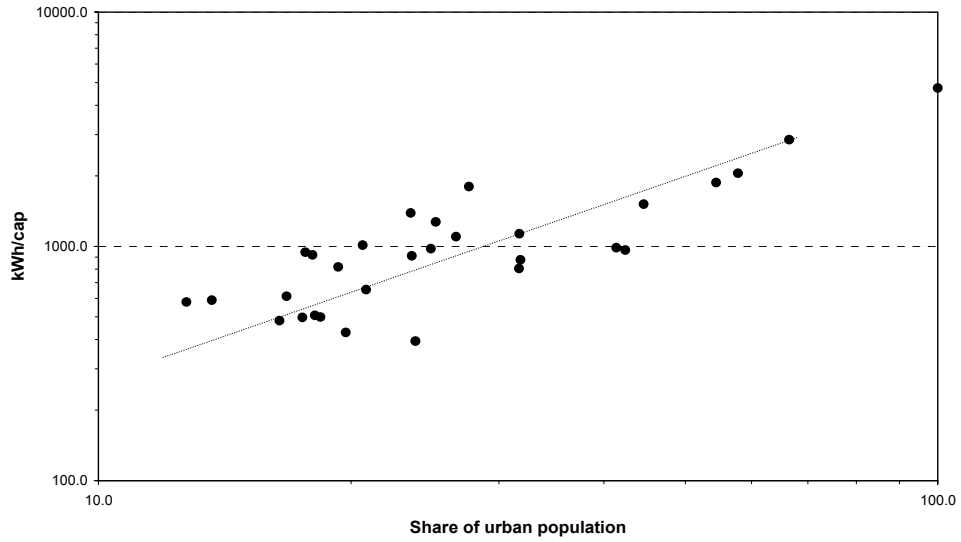
**Figure 9:** Consumption of electric power and net primary school enrollment ratio. Primary school enrollment (%net) is defined by the World Bank as “the ratio of the number of children of official school age (as defined by the national education system) who are enrolled in school to the population of the corresponding official school age. *Data source: World Bank Development Indicators (2002).*

### *Cross-section within Countries*

A second way to look at macro data is in cross-section within countries. The global data may not reveal inflection points because they are highly aggregated. Such within-country cross sections are shown in Figure 10 (China) and Figure 11 (India). These data, also, do not reveal any inflection points. They confirm that rural areas tend to have lower consumption of electric power; they also confirm that lower electric power consumption accompanies lower economic growth. It is interesting to note that about half of Chinese provinces *already* exceed the target of 1000 kwh per capita; moreover, all Chinese provinces that are more than 50% urbanized (e.g., Shanghai) exceed the target. These statistics confirm that what happens in China, the world’s most populous nation, will have an enormous impact on whether and how we meet world development goals—just as the remarkable progress in China over the last two decades is the main explainer for the success in reducing the incidence of poverty in the world

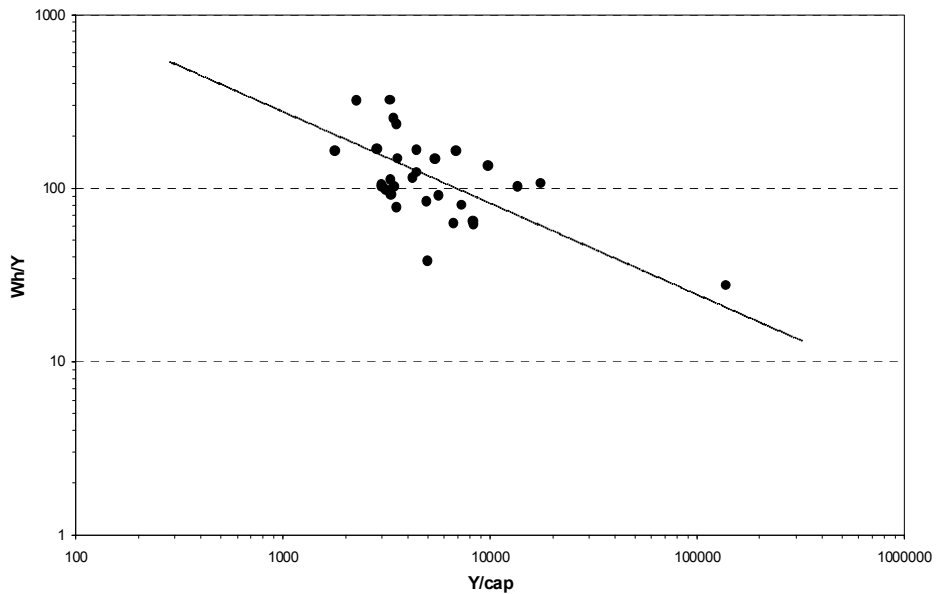
**Figure 10 (Panel A)**

**China: Electricity per capita versus share of urban population, by provinces, 1995**



**Figure 10 (Panel B)**

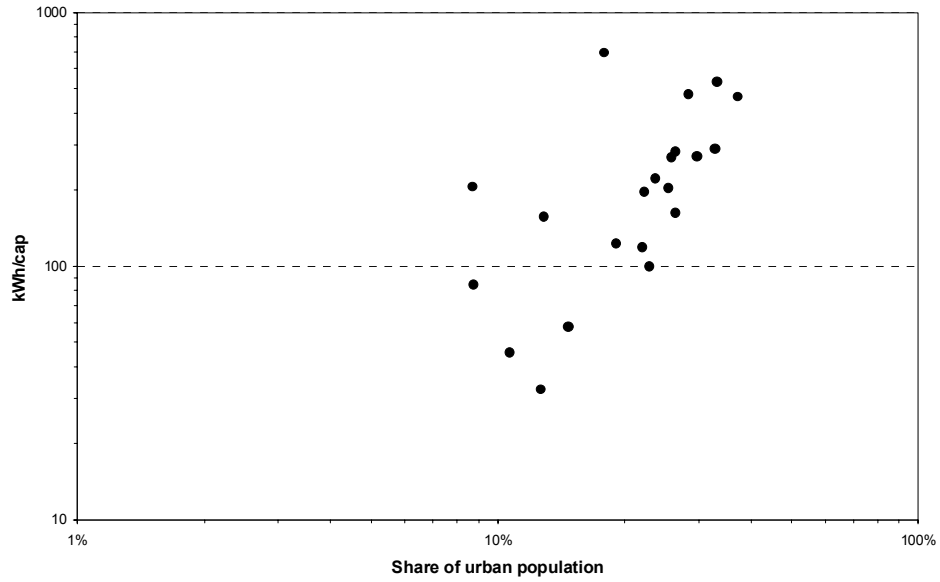
**China: Electricity Intensity of GDP versus GDP per capita, by provinces, 1995**



**Figure 10:** Cross section of electric power consumption in China as a function of urban/rural population (Panel A) and income (Panel B). Data points represent Chinese provinces; “Y” is yuan. *Source: China Statistical Yearbook (1997).*

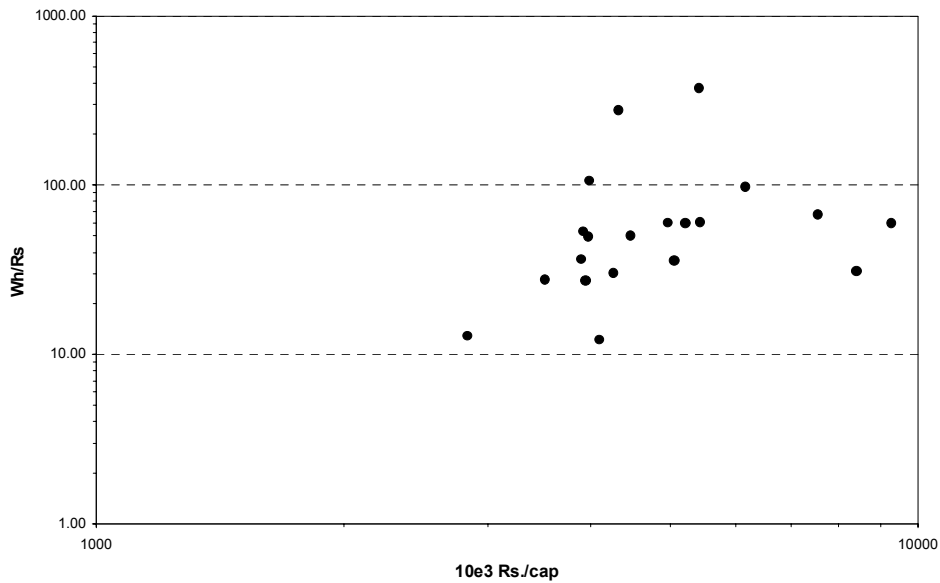
**Figure 11 (Panel A)**

India: Electricity Generation per capita versus Share of urban population, by provinces, 1991



**Figure 11 (Panel B)**

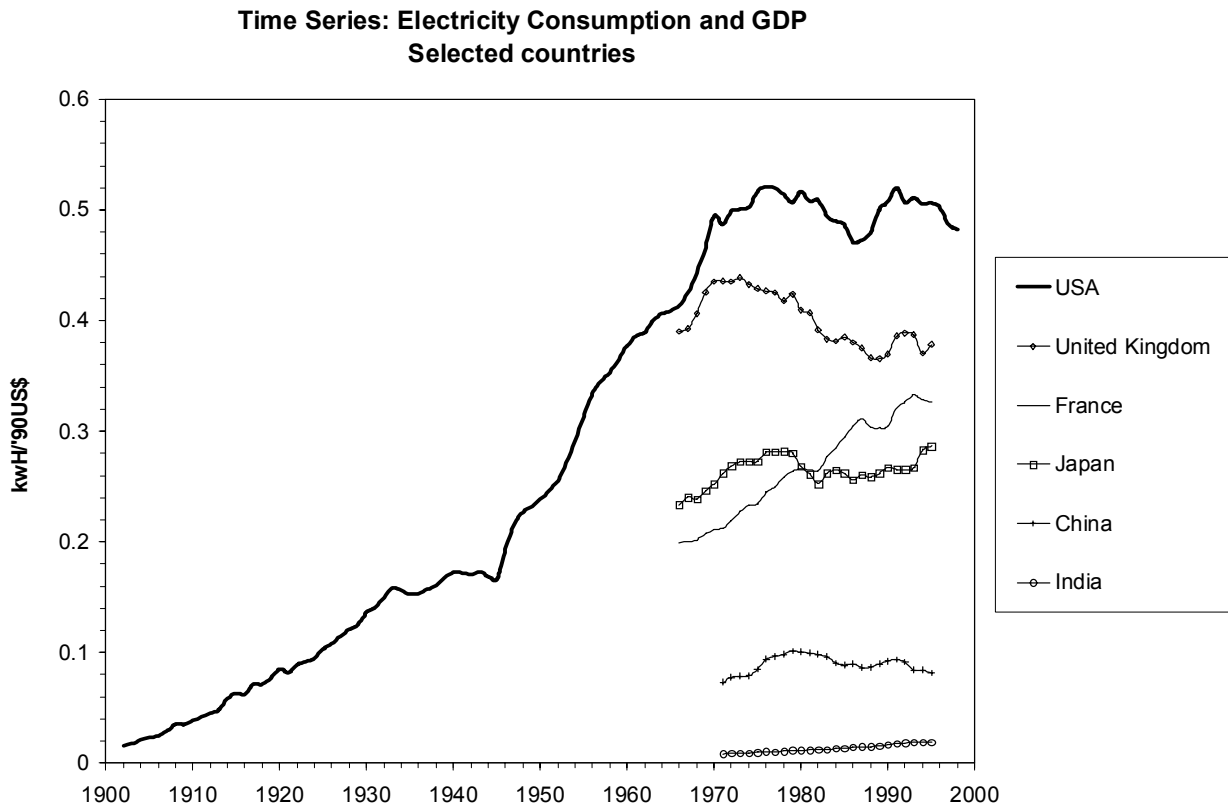
India: Electricity Generation Intensities versus GDP per capita, by provinces, 1991



**Figure 11:** Cross section of electric power production in India as a function of urban/rural population (Panel A) and income (Panel B). Data points represent Indian states; these data are for production, whereas figure 5 (China) reports consumption—we have been unable to secure reliable consumption data by state for India. *Source: CMIE 1995*

## Time Series

A third way to look at macro data is in time series. We have not found reliable time series for developing countries, so on Figure 12 we show the long data set for the U.S. and shorter data sets for other countries. These data are converted to common units using market exchange rates and thus allow a contrast with the data shown on Figure 8, which report PPP. It is not obvious which method to use, but the market exchange rate approach suggests greater variance in the relationship between electric power inputs to an economy and the outputs. Moreover, it suggests that the electricity required per unit of economic output actually *increases* with growth, which is evident in the long time series for the U.S. With industrialization the U.S. required a steadily rising input of electric input until the 1970s energy shocks leveled the trend. By this measure, the U.S. appears to be one of the least efficient of the advanced industrialized countries in converting electricity to economic output; by the PPP-based measure shown in figure 4 the U.S. is right on the trajectory of other countries, if not among the more efficient high-income nations.



**Figure 12:** Time Series data on Electric Power Consumption and Economic Output for selected countries. US Figures derived from Mitchell (1998); other countries as reported in World Bank Development indicators (2002). Note that economic output data are based on market exchange rates because PPP conversions (to allow comparison with figure 4) are not available before 1960.



These cross-section data reveal two things about setting targets for global electrification. First, they suggest that there is no inflection point or minimum quantum of electricity that could serve as a minimum acceptable or minimum average quantity. The benefits of electric power, measured as economic output, rise steadily from low levels to very high levels. Second, if the consumption of electricity rises steadily with economic growth then we can set some benchmarks for global consumption of electric power. Today's average per capita consumption is about 2100 kwh/capita, roughly the average level in Chile or Argentina. The average income in the world is about 5500 USD/capita (in 1995\$, converted using market rates). If average incomes rise at 3% per year over the next 50 years (roughly a quadrupling), which may be low in light of the spectacular performance of China and India in the last decade, then average electric power consumption would rise to about 9000 kwh/capita.<sup>13</sup> If the world population is about 9 billion at that time then the total power required will be approximately 81,000 TWH, or about double the power consumption today.

## V. Strategies for Electrification

Having outlined and defended some goals for minimum and average power consumption we now turn briefly to the question of how this power might be supplied, and the implications of the different supply options for the key capability gaps that must be closed in the coming decades. We look at these issues from two perspectives: (1) the experiences with building institutions for public and private electrification programs, and (2) the technical characteristics of the load and the systems that might meet the demand.

Before we look at policies, institutions and technologies, however, two points of context are essential. First, there is a tendency to think about deficits in energy services as problems that *energy policy* must solve. In reality, however, the most powerful channel for expanding energy access has been development. The 1990s estimate that 2 billion people lack access to modern energy services reflected not just the lack of institutions and infrastructures for supplying these people but also low purchasing power. Indeed, a new estimate will soon be published suggesting that 1.6 billion people now lack access to energy, with the decline due mainly to development in China. China has implemented some active electrification programs, but the main success in Chinese electrification stems from the success of Chinese development. From 1970 to 1990, in the three developing regions where economies generally grew—in Latin America, China and East Asia—about 650 million new people were connected to electric power service while the population

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<sup>13</sup> For comparison, a 3% per year compounded growth to 2050 would lift the World GDP to about 120 trillion (1990\$/yr). The IPCC SRES family of scenarios envisions a range of World GDP in that year from 82 trillion 1990\$/yr (A2 family) to 177 trillion 1990\$/yr (average of the three scenario groups in the A1 family). See Nakicenovic et al. (2000), table T3-2a. All of these values are somewhat higher than the assumption of 100 trillion 1990\$/yr in the EPRI 1999 roadmap (EPRI, 1999).

grew by only 280 million. In contrast, in the three regions where economies and institutions fared poorly—North Africa, Sub-Saharan Africa, and South Asia—population growth outpace electric service by about 250 million people (Jechoutek, 1997).

Indeed, it is essential that the task of electrification not be viewed in isolation from other development challenges. Today perhaps 2 billion people lack access to basic sanitation services; 2 billion also have little access to education. Nearly 2 billion live on less than \$2 per day, which is one measure of extreme poverty. These 2 billions are all, more or less, the same people; they are also the remaining engines of population growth. For 2 billion people, life is nasty, brutish, and short. Policies are needed to address each of the ills of these 2 billion, but the epicenter of policy making must focus on economic growth. A full recounting of strategies for promoting economic growth is beyond the task of this essay, but it is worth underscoring that the new emerging consensus emphasizes creating institutions for good governance, transparency, and rule of law rather than simply transferring vast sums of resources and technologies to countries in need. The new approach emphasizes creating internal conditions that favor investment and diffusion of new technologies; getting the conditions “right,” in turn, encourages a combination of private and public sector activity. These complementary development programs aid not only the general progress of development but also typically favor the emergence of institutions that are directly useful for electrification. For example, some semblance of rule-of-law and enforceability of contracts—at least informally if not formally through impartial administrative procedures and courts—eases the widespread diffusion of financial services, including “microfinance.” In turn, these financing institutions make it easier for households and communities to make the capital investments that are a hallmark of electrification—stoves, refrigerators, small generators, mini-grids, and so on.<sup>14</sup>

Second, a strategy for global electrification will require not only complementary policies for general economic development but also complementary policies for non-electric energy carriers. As we have seen, a defensible vision for global electrification depends critically on one’s vision for how to supply basic cooking and heating needs. One can achieve large benefits in terms of lower pollution and less local pressure on forests, for example, through more efficient cookstoves. In some areas where high electric power

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<sup>14</sup> On institutions for financing development, with attention to the informal rural sector, see Hoff et al., eds. (1993); for a comprehensive survey that focuses on what has become called “microfinance,” see Robinson (2001). The importance of well-functioning institutions—whether formal (e.g., independent courts) or informal—is one reason for the new insights into the effectiveness of development assistance. In a nutshell, the insight is that development assistance programs can be effective only when they supply resources into societies that have properly functioning governmental and non-governmental institutions, or if the resources are used to leverage changes in policy that cause those institutions to be built or reformed. Thus in countries that have “good governance” aid has had a large and positive impact; in those without good governance much aid has been wasted. (There are many other factors at work, such as government budgets that are not massively out of balance and exposure to international trade.) For more on the new thinking about the effectiveness of aid see Easterly (2001); Dollar (2001) and World Bank (2002).

densities are not feasible to supply, a strategy for sequencing electric power might focus on high-end uses and include a complementary program to diffuse advanced kerosene or LPG stoves into households so that houses are less plagued by particulate pollution without having to wait until higher purchasing power and electric supply systems allow for electric cooking and heating. Similarly, as communities plan their electrification strategies they must look, also, at the wide range of household, agricultural and industrial activities that electricity may serve. They may decide to combine biogas technologies with strategies for recycling crop wastes and managing agricultural nutrients. Similarly, they may combine diesel-powered generators for local mini-grids with power takeoffs for milling equipment. There is no single best “answer” for these complementary energy strategies, but the process of planning for and encouraging electrification must include a broader look at energy balances and electric uses.

### *The Experience with Electrification Institutions and Policies*

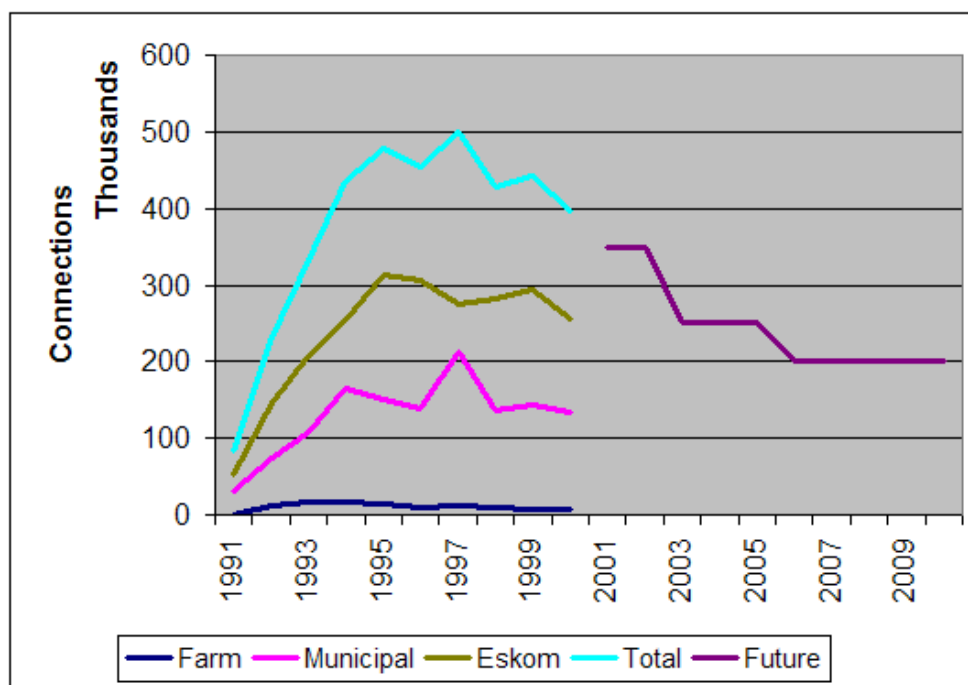
Broadly, efforts to diffuse electric technologies have fallen into three categories: (1) Programs to connect under-served households to the grid, implemented mainly by existing utilities; (2) Programs to establish or encourage creation of cooperatives, especially in rural areas; and (3) the emergence of private sector for-profit programs to electrify under-served areas. We address each in turn.

#### Grid-extension Programs

Most developing countries have active programs to connect under-served households to the grid. For most of the history of electric power, utilities have either been owned by government or at least regulated closely by government authorities. Governments have been able to order the extension of grid services even though, often, such rural extensions do not recover their cost. Typically, the cost of these extensions is paid by a cross-subsidy in which urban and industrial customers pay more than the cost of service and rural customers pay less. (Rural bills are still often higher, but they still typically do not reflect the full cost.) Such rural extension programs are pursued because they are vital parts of rural development and they are politically popular in rural areas where most people in the developing world still live.

To illustrate the practice of grid extension, we follow the illustrations from South Africa used earlier. Figure 13 shows the number of connections as part of South Africa’s active electrification program; most of the connections are supplied by the utility (Eskom) and by municipal governments that control local power distribution. Some connections are made through farm cooperatives. Comparing those results with Table 2 shows that as more households have been connected the cost has declined. This reduction appears to be a learning effect as the electrification program has extended to areas further from the grid—where costs would have been expected to rise without such learning.

The fate of these programs during the “restructuring” of electric power markets is quite unclear (Dubash, ed., 2002). In principle, restructuring to make power suppliers more responsive to market forces will undercut the incentive to extend energy services to rural and poor areas. In societies that want to provide such services, rules will be needed to steer the market—for example, subsidies for rural service, competitive bidding for rural service subsidies, and vouchers that lift energy purchasing power in rural areas (e.g., Winkler and Mavhungu, 2001; ESMAP, 2000). But none of these programs is easy to implement. Explicit subsidy and voucher programs require on-budget expenses that might be politically difficult to sustain especially in hard times when government budgets are squeezed. Cross-subsidies, such as through requirements that distributors serve a combination of wealthy and poorer customers with the former subsidizing the latter, are prone to unravel as the higher paying customers find ways to segregate themselves into a separate market. Moreover, some of the incentives for rural electrification have occurred by tolerating non-payment or under-payment of bills; as discovered in India, where this practice is rampant, political difficulties follow when market reforms give suppliers an incentive to crack down on this practice.



**Figure 13:** Number of household connections per year in the South African electrification programs. Data show connects from Municipal electrification programs and also the Eskom program, as well as projections for future connection. *Source: Lloyd (2001) from data reported by the South African Ministry of Mines and Energy.*

## Cooperative Electrification

Although advocates for electrification of the under-served households often look to the supposedly deep pockets of integrated utilities, much of the success with rural electrification has occurred in the hands of co-operatives. Although, in practice, it is difficult to draw a fine line between a government owned utility and a cooperative, the cooperative approach relies on the beneficiaries of the service to initiate the supply, but the cooperative is often a self-standing entity rather than a charity or other organization that relies on continual outside funding (e.g., see the experience in Costa Rica reported in Monge, 1997). Where purchasing power is adequate (or supplemented by grants or subsidies) and institutions allow these cooperative approaches to emerge they have flourished. Much of the rural United States was electrified through cooperatives (with subsidies and mandates); a substantial fraction of U.S. power supply is still delivered to homes and farms by cooperatives. In developing countries, small-scale cooperatives have purchased generators (e.g., run-of-river small hydro) and established small grids—for example, run-of-river small-scale hydro generation in rural Dominican Republic. Successful cooperative programs have established partnerships in other countries to spread the model (e.g., NRECA, 2002; Inversin, 1986).

## Private Sector Electrification

Until recently, the private sector has not been the first stop for peoples and governments that sought electrification of the least well-served communities. Indeed, the populations that are least well served by electricity tend to be in countries where an entrepreneurial private sector is least active—in part, that is why those areas remain stuck in poverty traps that keep purchasing power depressed. Moreover, electrification has not been a good candidate for private sector investment for at least two reasons. First, grid-based electrification requires large and costly infrastructures that are difficult to site, protect and operate. These infrastructures traditionally they have been the province of state-owned utilities. Investments in costly assets that yield economic return only over long time periods tend to be poor candidates for private profit-seeking enterprises when the host country lacks the “rule of law” that is needed to ensure that valuable assets are not nationalized or stolen once they have been constructed and demonstrated their value. Second, the rural poor are not usually associated with purchasing power that is adequate to profit-making ventures; indeed, as suggested in Table 2, even large-scale electrification that allows for cost-reductions through learning barely covers its operating expenses and probably does not cover capital costs using normal commercial criteria.

Both these factors that have deterred private sector investment are changing. Increasingly it is attractive to pursue small-scale electrification through mini-grids and stand-alone household systems. These technologies make it possible for private sector investors to yield a profit without being required to build entire large grid infrastructures. The cost of these small-scale approaches has declined sharply, in part because of

improvements in renewable energy generation technologies such as windmills, biogas generators and solar photovoltaic household and mini-grid systems. Firms that fashion themselves as energy services companies are in a position to sell high-value energy services to households that have revealed that they are willing to pay very high prices for those services—especially electric power, where households in some areas appear to pay \$.5 per kilowatt hour (or more) for their first monthly kilowatt hours. Technological and institutional changes are transforming electric power supply from a charitable or unprofitable venture to one that could spread through market forces alone.

Examples of these programs include Shell’s effort to connect villages to solar photovoltaic electric supply, which remains unprofitable by standard commercial measures but is supported by the firm, in part, because of the hope that learning effects will reduce costs. EDF has launched a venture in Mali (and now expanding to other countries) that supplies rural homes with solar energy services (passive heating as well as electric). They have built a financial model that allows for optimization of systems using mini-grids (where loads are relatively dense) and stand-alone solar homes. The system is reported to be profitable using standard rates of return, provided that the risk premium for operating in the country is not charged. (EDF absorbs that premium itself.) For the outside analyst, it is difficult to assess the extent to which these programs are supported by these firms because they confer certain political and reputation advantages as opposed to their true promise as independent profitable ventures.

Although private sector electric services remain a tiny part of poor rural supply, they suggest that from the perspective of the 50 year time horizon that the electric power system might evolve to a business model that is similar for most other basic energy services such as charcoal, kerosene and LPG. The private sector might supply them and policy, if needed at all, would aim to alter market incentives.

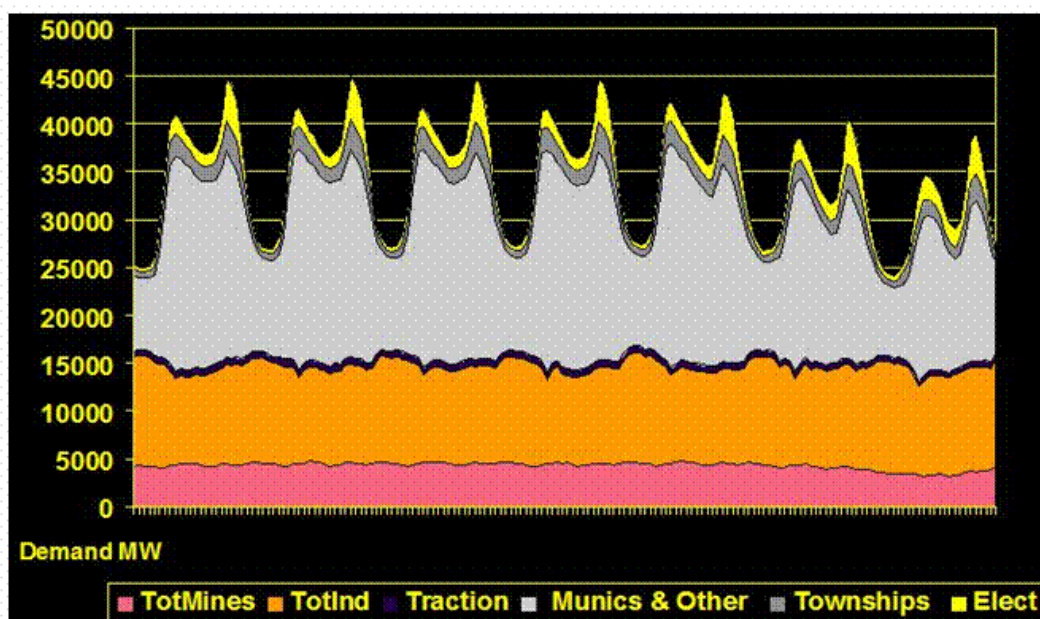
### *Technical Characteristics of Electrification Programs*

Finally, we provide a brief review of the technical characteristics of the load and the technologies that supply that load. Those characteristics, along with the discussion that has gone before, will help to identify key R&D needs for the future. Considering those R&D needs is the principal purpose of the workshop for which this essay serves as a background paper, and a separate document outlines an initial set of “Critical Capability Gaps” that could inform an agenda for R&D. The workshop will alter and elaborate those gaps and will focus on which institutions should perform the different tasks that will be needed to close the gaps.

### Peak Loads

Because the task of global electrification consists mainly of providing electric services to households, the load profile from successful electrification efforts is mainly a

function of household activity. The initial kilowatt-hours are spent on high value activities that tend to vary sharply during the day rather than yield a level base load. Television and radio loads tend to occur throughout the day, especially after normal working hours; lighting occurs in evening and at night. An electrification program that includes only these services would tend to have a level load with an evening peak, which could offset daytime peaks in the rest of the economy. But an electrification program that includes heating water and cooking will cause much sharper peaks around mealtimes, with the afternoon peak coupled to evening demands for entertainment and lighting. Indeed, those patterns are revealed in Figure 14, an estimate for the typical load profile during a winter (peak) week in the year 2015. The profile shows steady loads for manufacturing and mining operations, which drone 24 hours per day and sharp peaks caused by municipal electrification programs and the nationwide electrification program.



**Figure 14:** Estimated peak load for typical winter week in 2015, South Africa. Baseload from mining and industry is little changed from current levels and demonstrates little diurnal variation. Nearly all growth in capacity requirements is due to afternoon peak load in townships, municipalities and from the electrification program designed to connect more households to the grid. *Source: Eskom internal forecast.*

Since the capital requirements for generation, transmission and distribution are the main cost of grid-based electrification (see Table 2), strategies for more rapid and cost-effective electrification will require attention to leveling the load. Timers on water heaters, peak pricing and other approaches may be useful; studies should look at how the cost of those efforts compare with the capital cost of new capacity. It may also be useful to link

household electrification programs with active efforts to electrify other loads that are (or could be) variable. For example, household electrification might be coupled with electrification in agriculture, with water pumped at night and stored in tanks.

### Decentralization of Supply and Demand

Although development leads to urbanization, today's projections for the next three decades suggest that the size of the (poorer) rural population in developing countries will remain roughly constant at about 3 billion. The task of ensuring that minimum goals for electrification will be served will be mainly a rural one. In rural areas, perhaps even more than for urban electrification, decentralization of energy services is important because of the very high cost of distribution infrastructures. Decentralization can occur in terms of supply—mini-grids or stand-alone homes, as in EDF's electrification program in Mali—as well as demand. Important technical and economic issues with a decentralized system—for example, the optimal allocation of investment between generation and distribution infrastructure, on the one hand, and improving efficiency and load profile of end-use on the other. But political and institutional issues may be equally important. For example, there is anecdotal evidence that decentralized electric power systems based on renewable energy sources have been resisted by users because of fear that non-grid systems are less scalable to high power uses than are firm connections to the grid. For example, solar PV systems used for rural electrification are adequate for a few lamps and a radio but not scalable to include electric cooking; mini-grid systems based on renewable power (e.g., small scale hydro, biomass generators and co-generators) may be more scalable and acceptable. If societies pursue options that are not easily scalable then the goals discussed in this paper, at least with present technology, may not be achievable—many of the clean energy services we envision that could be supplied by electricity would require alternative energy carriers.

### Power Quality

Finally, the quality of power in the underserved served areas of the world is generally poor—for grid- and non-grid services. Interruptions are common and often lengthy; frequency control is poor. However, it is hard to draw generalizations about the relative reliability of grid and non-grid systems. The systems are highly diverse, and not all of the causes of poor power quality are technical. Institutional factors, such as incentives to supply reliable power and incentives to control theft (which, in turn, affects the ability of grid managers to control frequency and outages), often play the dominant role.

Looking forward, one of the key unknowns is the level of quality that will be required and how best to serve it. The future uses of electricity, even for households at the minimum acceptable level, are likely to include sensitive equipment such as computers. Indeed, at the same time that the electric power industry is considering its proper role in



global electrification, governments and the computer industry are looking for effective strategies to narrow the “digital divide.” If they succeed then the future level and quality requirements for electric power even in poor rural areas might be driven by the need to supply computing technology—which is already true in many highly developed areas and could be the norm in 50 years worldwide. Decentralized storage and power conditioning could address these power quality requirements—even by brute force (e.g., batteries). Or it might be more economical to develop and apply sophisticated real-time control on supply and end uses that work in the conditions found at rural electric systems.

## **VI. Conclusion**

This paper outlines and defends some goals for electrification of the world over the next 50 years and focuses on goals for minimum quantities of electric power supply. It is part of a strategic planning exercise within the Electric Power Research Institute’s *Electricity Technology Roadmap* that is focusing on the key “capability gaps” that must be filled by the industry, governments and the research community in the coming decades. Based on this paper, a separate document outlines, in bullet point format, major capability gaps and suggests some research needs. Here we conclude by focusing on a few that appear to be particularly important.

First, we offer here only an initial outline and defense of some targets. More work is needed to look at the targets and describe better the interactions between the targets and a wide array of technological changes. The 1000 KWH/person/yr goal could be much smaller with improvements in end-use efficiency and with integrated development strategies that focus on multiple fuels. The feasibility and economic tradeoffs require analysis. More work is also needed to develop goals that are appropriate for particular regions and settings, not least because the cultural determinants of fuel and technology choice as well as heating needs vary considerably. One size probably does not fit all. But as a first assessment, this essay suggests that the order of magnitude for the global goal of minimum supply should be 1000 KWH/person/yr.

Second, the success in this endeavor depends not only a large number of technological issues but also a complex array of institutional factors. Through cooperatives and private markets, even poor communities serve some of their energy needs. Technological change could allow such collective and market-based approaches to serve basic needs even more fully. However, the success of these market-driven approaches depends critically on the existence of institutions that allow for pooling of resources and collective financing, enforceability of contracts, and a long-term perspective on development. The success of overt programs to transfer technologies into under-served areas also depends on those same institutional conditions. Yet very little of the systematic research on the institutional determinants of development has focused on the role of

institutions in the energy system. That omissions is striking in light of the critical role of energy services in development and the fact that costly energy infrastructures and services are an ideal case for exploring the impacts of institutions.

Third, from the experience with existing electrification programs we can derive at least two important lessons. One is that purchasing power is critical to achieving the goals set here. Much of the debate over energy for the poor has been framed only in terms of “access,” but that is incomplete because access is only part of the equation; often it is essential to subsidize access to energy services, but distortions occur when programs attempt to subsidize consumption (e.g., see ESMAP, 2000). Purchasing power is unavoidable. The other evident lesson is that the technical characteristics of the load are important. Electrification can yield peaky loads; success in leveling those loads could make resources spent on electrification go much further. Moreover, there are important tradeoffs between resources spent on extending access and those spent on assuring power quality and reliability. More work is needed to understand and model the power quality needs and how they intersect with global electrification, especially as computer technologies spread rapidly worldwide and may impose higher power quality needs than were the norm in past efforts to electrify the world.

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