Energy Transitions in Developing Countries: a Review of Concepts and Literature

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Abstract

The Industrial Revolution accompanied a dramatic change in energy systems, away from locally gathered, traditional fuels such as biomass to commercially traded fossil fuels. For nearly 2 billion people in the world today, this commercial energy transition is yet to occur. We review the literature on the causes and consequences of this transition and the effectiveness of policy instruments aimed at accelerating or directing the transition. Income is the main driving force, but other factors—such as population density and the availability of rival fuels—affect energy choices. Although correlations between the energy transition and economic growth are high, cause and effect relationships have proved difficult to establish.

Keywords: household energy, biomass, cookstoves, health effects, economic development

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1. INTRODUCTION

Throughout history, the ways in which humans have mined and manipulated resources to extract energy have been ever-changing. Before the advent of organized agriculture, energy was used sporadically for cooking and heating when biomass could be foraged locally. Around 10,000 years ago, the Neolithic revolution ushered in a transition in energy technology that facilitated the shift from hunting and gathering food to organized agriculture (Snooks, 1994; Diamond, 1999).[1] As time was freed from gathering food and fuelwood, the organization of society shifted from small and self-sufficient groups to larger settlements of specialized, interdependent producers (Seabright, 2004). A class of non-food producers—craft specialists, merchants and soldiers—emerged; the egalitarianism of hunter-gatherer groups gave way to increasing stratification and centralization of power (Hassan, 1979). Continuous improvements in agricultural tools and techniques increased surplus crop production and allowed a sharp rise in global population and settlement in larger communities (Childe, 1942; Hassan, 1979).[2] Agriculture offered not only a standing source of food, but a ready source of biomass energy (crop waste). The role of biomass in energy budgets rose, along with the motive power of domesticated animals—which in turn allowed for more intense cultivation of crops (Landes, 1999).

Until the Industrial Revolution, almost every society obtained nearly all of its energy from site-specific resources. Biomass was burned for light and heat, and animate sources of power—humans and draft animals—supplied most mechanical energy, supplemented increasingly with wind and water power (Grübler, 1998). Nearly all biomass was converted for final use in inefficient devices nearby, such as open and stone-ringed fireplaces. Some specialty applications such as kilns for pottery making and the casting of bronze used large quantities of primary energy—and some of these devices were highly efficient—but most energy went for tending crops and for cooking and heating dwellings.[3] Dwellings helped to contain the heat, but also the pollution.

Human society is now in the midst of another transition in energy systems that, as with the Neolithic revolution, is occurring alongside dramatic changes in social and economic organization and a rapid rise in global population. The Industrial Revolution, which dates to the late-18th century and has spread throughout the West, signaled a series of changes in the way humans quarry and consume energy. In this new energy transition, fossil fuels have come to dominate primary energy supply.

Fossil fuels, first coal, offered much higher energy densities and more flexibility than the bulky and site-specific resources that dominated the pre-industrial era (Grübler, 1998). Coal and steel powered both mass production and low-cost transportation (by rail and steamship) of industry products (Atack et al., 1980).[4] Trade allowed localities poor in energy endowments to seize the advantage of fossil power and also greatly accelerated the diffusion of industrial innovations.

Britain, birthplace of the Industrial Revolution, saw a succession of innovations in the use of steam power between 1770 and 1870 (Landes, 1999). Steam was particularly important to mining (coal, copper and lead) and to powering the factories that drove the boom in Britain's textile industry (Mokyr, 1990). In the U.S., coal production climbed from 7.5 million metric tons (mmt) in 1850 to over 455 mmt in 1910, expanding industrial output and enabling long-distance transport of people and products (Mitchell, 1998).

While much of this revolution occurred within industrial firms—part of a broad reorganization of economic activity that saw production shift from households and small farms to industrial enterprises that eventually became organized as factories—the modern energy transition has also affected households. Coal replaced wood and agricultural wastes for interior heating—either directly or as steam supplied in distant heat schemes. Later, new fossil fuels—oil and natural gas—supplanted coal, preferred for their higher energy densities, ease of transport and relative cleanliness (Mitchell, 1998).[5]

This transition to more efficient, commercial energy sources and technologies is still unraveling throughout the developing world. Roughly 2 billion people worldwide still lack the benefits borne of commercial energy.

Massive improvements in human welfare have gone hand-in-hand with the modern energy transition. But the transition, though fundamental to the role of energy in modern societies, has posed at least three interlocking problems for analysts. First, the concept of an "energy transition" is wooly and difficult to define. Second, in the absence of clear definitions it has proved difficult to quantify patterns in the transition. Third, and most important, is the difficulty assessing cause and effect between the supply of modern energy services and improvements in human welfare. While standard measures of welfare—such as income and human health—have all improved alongside this transition, which way do the causal arrows run? The answers matter not only for scholars of economic growth, but also for the 2 billion people who still rely largely on biomass to meet their energy needs.

We review the large body of literature that relates to the causes and consequences of the modern energy transition. We focus on both macro and micro-level energy patterns, but pay particular attention to the household level; it is the household that ultimately makes fuel choices and whose welfare is ultimately affected.

We begin with definitions (part 2), then examine correlations between energy and economic indicators at the macro level (part 3). Then we turn to the micro level to explore the relationship between income and the energy transition (part 4). We then look at patterns in variables other than income (part 5) that may help fully explain the observed patterns in energy services. Finally, we explore the implications of the energy transition for human welfare (part 6) as well as policies that have sought to speed or direct the transition (part 7).

2. METAPHORS AND DEFINITIONS

Until a decade ago, most scholarship used the concept of an "energy ladder" to explain how households selected fuels and energy technologies (Leach, 1992; Barnes and Floor, 1996; Smith, et al., 1994). By that logic, traditional biomass fuels and primitive technologies reside on the lower "rungs" of the ladder; kerosene, liquid petroleum gas (LPG), natural gas and electricity (among other energy sources) occupy higher rungs. As incomes rise, households metaphorically ascend the ladder because modern energy carriers are preferred for their high levels of efficiency, cleanliness and convenience of storage and use relative to crop residues, dung, firewood and other traditional biomass fuels. Similarly, more efficient (though expensive) conversion technologies (such as low-smoke cookstoves) are favored over stone-ringed fireplaces and other traditional technologies. Studies have attributed varying degrees of importance to variables such as level of local infrastructure, relative fuel and technology prices and the reliability of different fuel systems; nearly all studies in this genre, however, assign primacy to income as the dominant propeller up the ladder (ESMAP, 2003; Leach, 1992; Pachuari, 2004; Tiwari, 2000).

However, a growing body of empirical studies on household energy use reveals that the energy transition does not occur as a series of simple, discrete steps; rather, multiple fuel use is common. With increasing affluence, households adopt new fuels and technologies that serve as partial—rather than perfect—substitutes for more traditional ones (Masera, et al., 2000; Leiwen and O'Neill, 2003; Eberhard and Van Horen, 1995; IEA, 2002). In urban areas of Guatemala, for example, the simultaneous use of firewood and LPG for cooking is quite common (ESMAP, 2003). In rural China, biomass and electricity are the most common fuel pairing in households (Leiwen and O'Neill, 2003). And in Brazil, although firewood's fraction of fuel budgets falls as incomes rise, woodfuel use continues even at relatively high income levels (de Almeida and de Oliveira, 1995). Only at the highest income levels do fossil fuels and electricity usually account for nearly all energy.

The more nuanced metaphor of "fuel stacking" is gaining support (Masera et al., 2000; Leiwen and O'Neill, 2003; ESMAP, 2003; Pachuari and Spreng, 2003). Although poor households often use several fuels simultaneously, they generally shift towards the adoption of cleaner, more efficient energy carriers as incomes rise. Multiple fuel use arises for several reasons. First, households often have significant capital invested in "traditional" technologies (e.g., wood-burning stoves) and may not have the spare capital to purchase new energy-consuming appliances immediately upon gaining access to new energy sources (Saghir, 2004). Second, modern energy sources are usually expensive and thus applied sparingly and for unique services (such as radios and television for entertainment) rather than simply supplanting an existing energy carrier to provide an already supplied service (Thom, 2000). Thus, traditional fuels and technologies tend to exit more slowly than new ones arrive; modern transistor radios exist alongside primitive cookstoves. Finally, multiple fuels can provide a sense of energy security. Complete dependence on commercially-traded fuels leaves households vulnerable to variable prices and often-unreliable service. Households in Hyderabad, India, for example, experience an average of two or three power outages each day (ESMAP, 1999).

While the "ladder" and "stacking" metaphors differ in their conceptions of precisely how energy sources are adopted, both recognize that hierarchies in household energy *services* are quite common. Almost always, cooking and heating are the first functions fulfilled, followed by lighting and later entertainment. For the poorest people in developing countries, cooking (and space heating in particularly cold climes) can account for upwards of 90% of the total volume of energy consumed; lighting accounts for the majority of the remaining share (see, for example, Howells et al., 2003). Appliances such as electric irons, refrigeration devices and water heaters arrive in household energy budgets only after core heating, cooking and lighting services are satisfied (Victor, 2002). Thus, the first kilowatts of *electricity* acquired by households are commonly used for lighting, entertainment and communication services, while many households continue to cook and heat the home with traditional fuels long after modern energy enters the household (IEA, 2002; WEC/FAO, 1999). Taste preferences and the familiarity of cooking with traditional fuels and technologies contribute to the tendency of cooking to be the last energy service supplied by modern fuels. In India, for example, many wealthy households retain a biomass stove for baking traditional breads (Malhotra et al., 2000). And in certain regions of Mexico even high-income households cook tortillas over an open wood fire rather than using an LPG stove because they prefer the taste and texture provided by woodfuel cooking (Masera et al., 2000; Saatkamp, 2000).

While considerable uncertainty remains in the literature on the energy transition, three key characteristics of the transition can be identified. First, the energy transition entails a simultaneous change in primary energy sources (e.g., biomass or LPG) and the technologies (such as cookstoves) that transform primary energy into usable forms—such as heat at the bottom of a pan. Second, these new fuels and technologies are typically not available locally because they require production with specialized technologies and in specialized facilities—LPG, for example, requires an infrastructure of petroleum production as well as fuel bottles, refilling services and stoves.[6] Engaging in such trade requires money, and thus the energy transition should be coincident with a rise in disposable income and how households spend money—the household money budget.

Third, the driving force for this transition seems to be internal to the household—the desire for more flexible energy sources is rooted, it appears, in the desire to free time for tasks other than gathering fuel and tending fires, as well as cutting the adverse health effects of traditional energy services (Chakrabarti and Chakrabarti, 2002). Thus, the energy transition should be evident in household time budgets and in measured health effects. The effects of the transition may also be most measurable in the time budgets of women since, as we will show, most of the labor and health burden of traditional energy is borne by females.[7] While these three measures—fuel and technology choices, household money budgets, and time budgets—should be highly correlated with changing energy use patterns, data at the household level, which is particularly important for assessing the links between energy use and welfare of the very poor, is notably absent.

3. ENERGY AND ECONOMIC DEVELOPMENT: MACRO PATTERNS

Most scholars studying energy use patterns have undertaken analysis at the national level. Ample evidence from cross-country data correlates energy consumption and economic prosperity (see Figure 1), and time series data shows that within countries, too, aggregate energy consumption has risen together with GDP (see Figure 2).

Rising GDP per capita is also accompanied by a shift away from biomass and towards fossil fuels and the widespread use of electric power. In the U.S., for example, between 1800 and 2000 biomass consumption per capita decreased to an almost negligible amount as economic development proceeded apace (Victor and Victor, 2002).

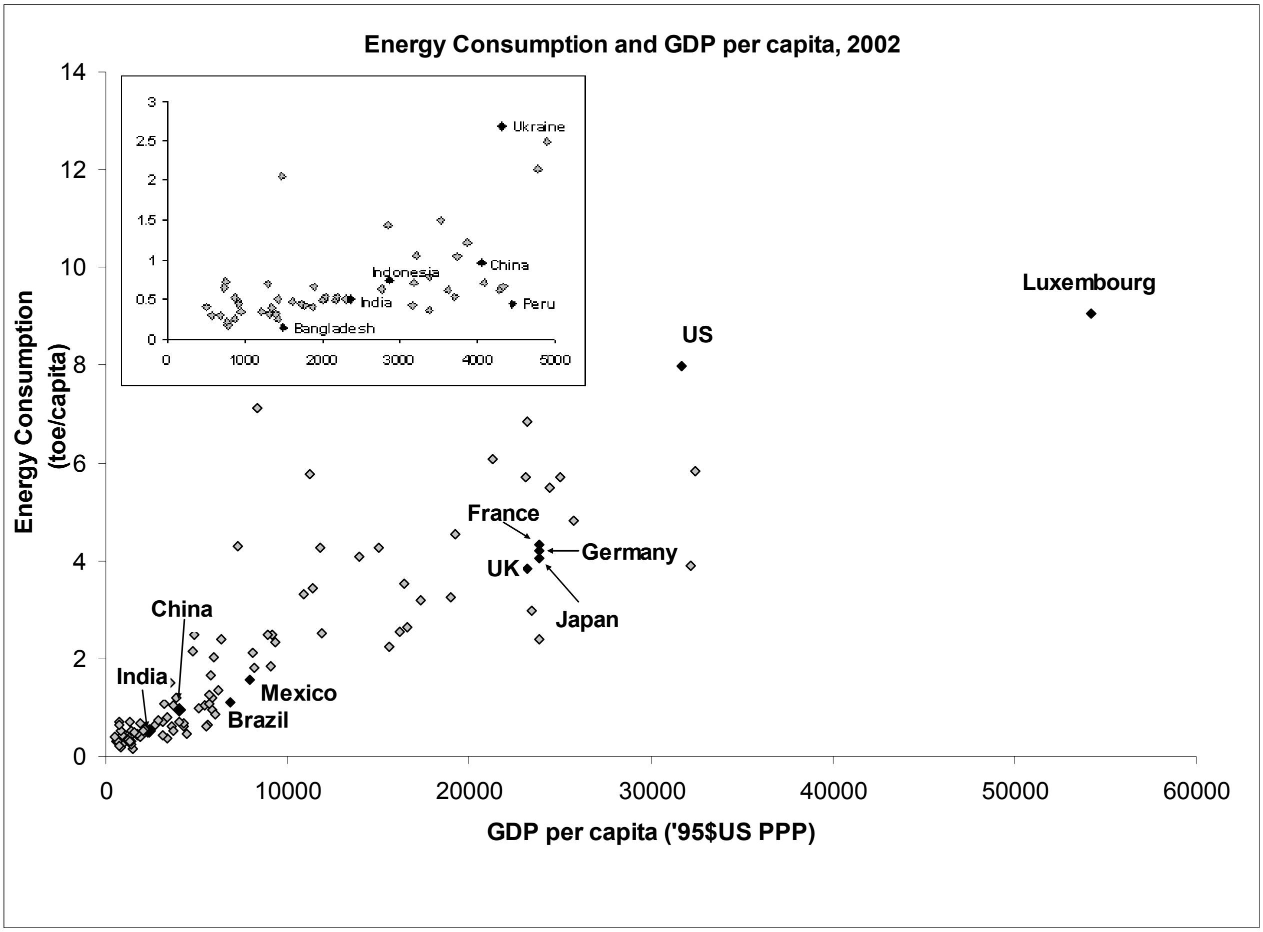

Figure 1: Energy consumption and GDP, 2002. Inset: countries with GDP below US$5000 (‘95US PPP). Rising GDP is generally accompanied by increased energy consumption per capita. *Source: IEA Key Energy Statistics 2004* Note: Primary energy sources are converted to common energy units, metric tons of oil equivalent (toe). This data set excludes locally collected traditional energy sources and thus partly under-states energy consumption at low income levels.

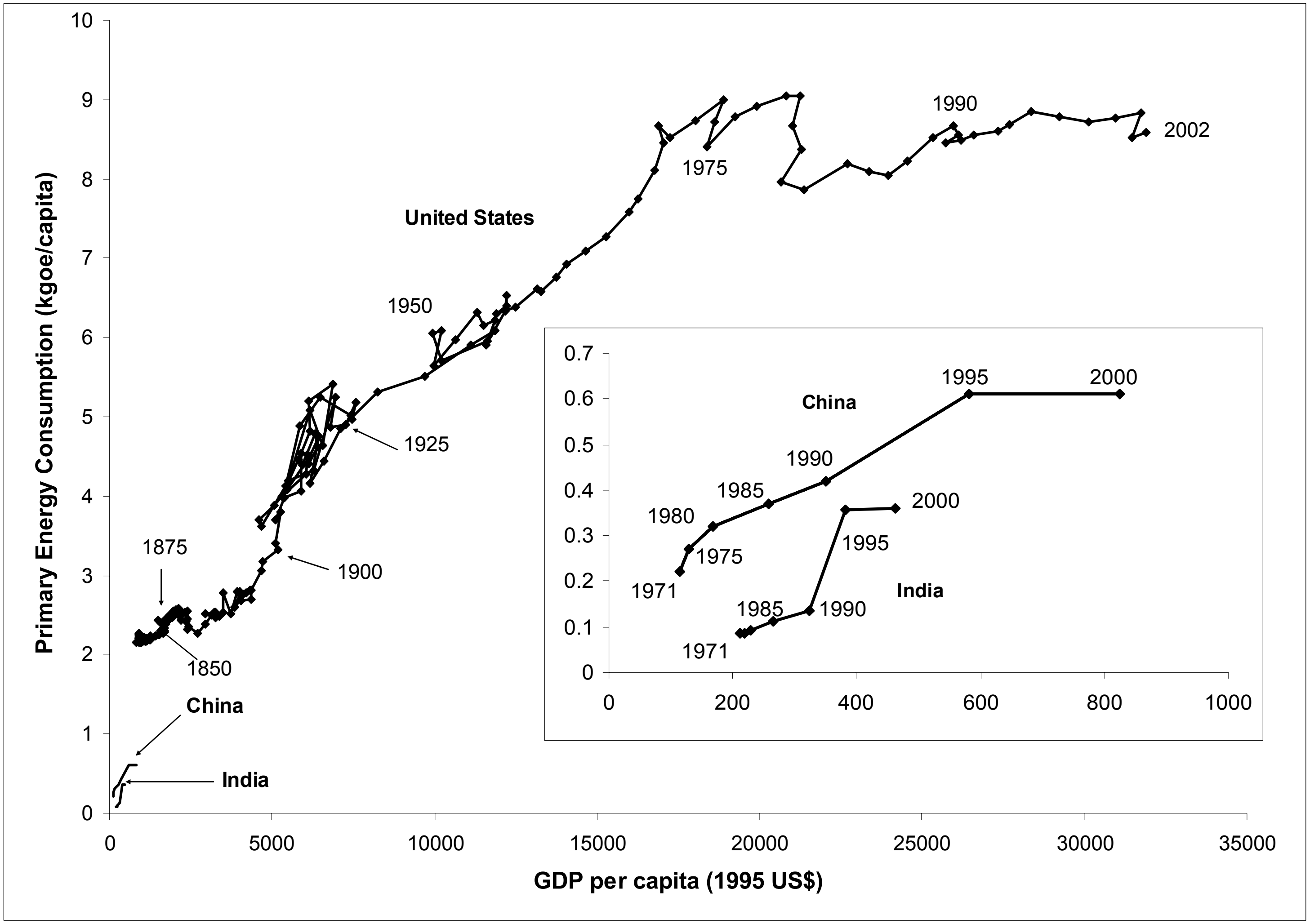

Figure 2: Energy consumption and economic growth over time in the United States, China and India. The U.S. shows a rapid rise in energy consumption per capita, relative to GDP, from around 1870-1910, which coincides with the Industrial Revolution. Today's developing countries tend to see the growth of primary energy consumption slow at lower levels of GDP per capita than did today's developed nations, due largely to their ability to leapfrog to more modern, efficient energy technologies. *Source: adapted from: Historical Statistics of the United States: From Colonial Times to the Present; IEA Energy Statistics, 1970-2002; Energy Information Administration (EIA), annual data; Mitchell, 1998 Maddison, 2001; and World Bank Development Indicators, 2004.*

While total primary energy use generally rises with income, the two do not move in lock-step. At early stages of economic development, the dominance of inefficient fuels and technologies means that large inputs of energy are required for the production of income. As economic development proceeds and more modern, efficient fuels and technologies are adopted, energy intensity—energy input per unit of economic output—begins to decline (see Figure 3). This general downward trend in energy intensity may be interrupted as a country enters the first stages of industrialization and material-intensive manufacturing becomes the dominant economic driver—such as in the United States from 1890 to 1930 (Grübler, 2004). Eventually, a post-industrial—service-oriented—system of production emerges in which natural resources are sipped even as measured economic output swells (Judson et al., 1999; Galli, 1999).[8]

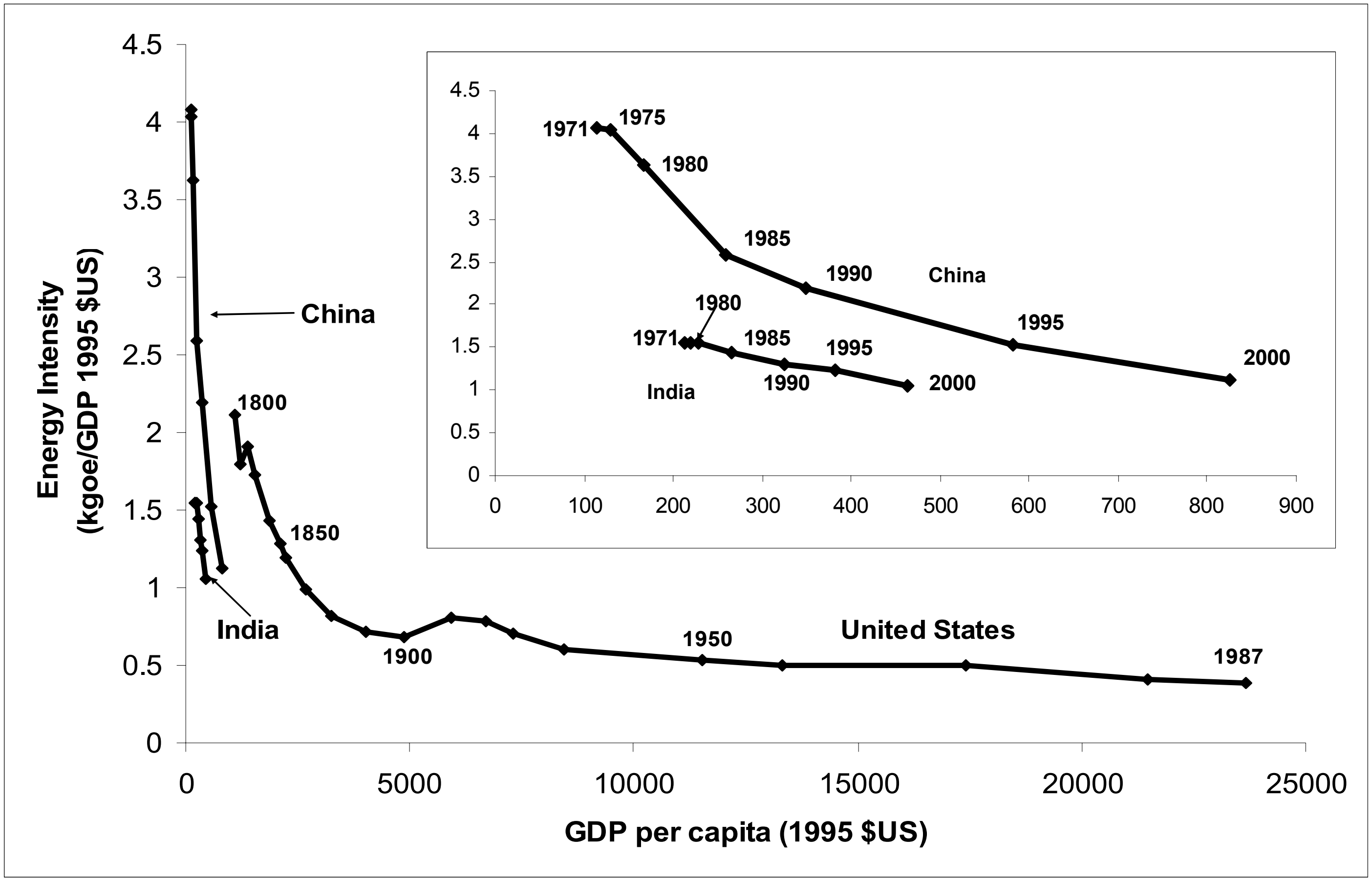

Figure 3: Energy Intensity and GDP. As GDP per capita increases, total energy intensity—energy consumption per unit of GDP—shows a general declining trend. This downward trend can be attributed to the increased efficiency of fuels and energy conversion technologies and a shift in the sectors that dominate the economy (away from industry and towards service-oriented enterprises), as well as decreasing income elasticity of demand for energy at the household level. Today's developing countries see reductions in energy intensity at much lower levels of GDP per capita than did the world's early industrializers—due largely to the increased availability of more efficient technology through international trade. *Source: adapted from: Historical Statistics of the United States: From Colonial Times to the Present; IEA Energy Statistics, 1970-2002; Energy Information Administration (EIA), annual data; Mitchell, 1998 Maddison, 2001; and World Bank Development Indicators, 2004.*

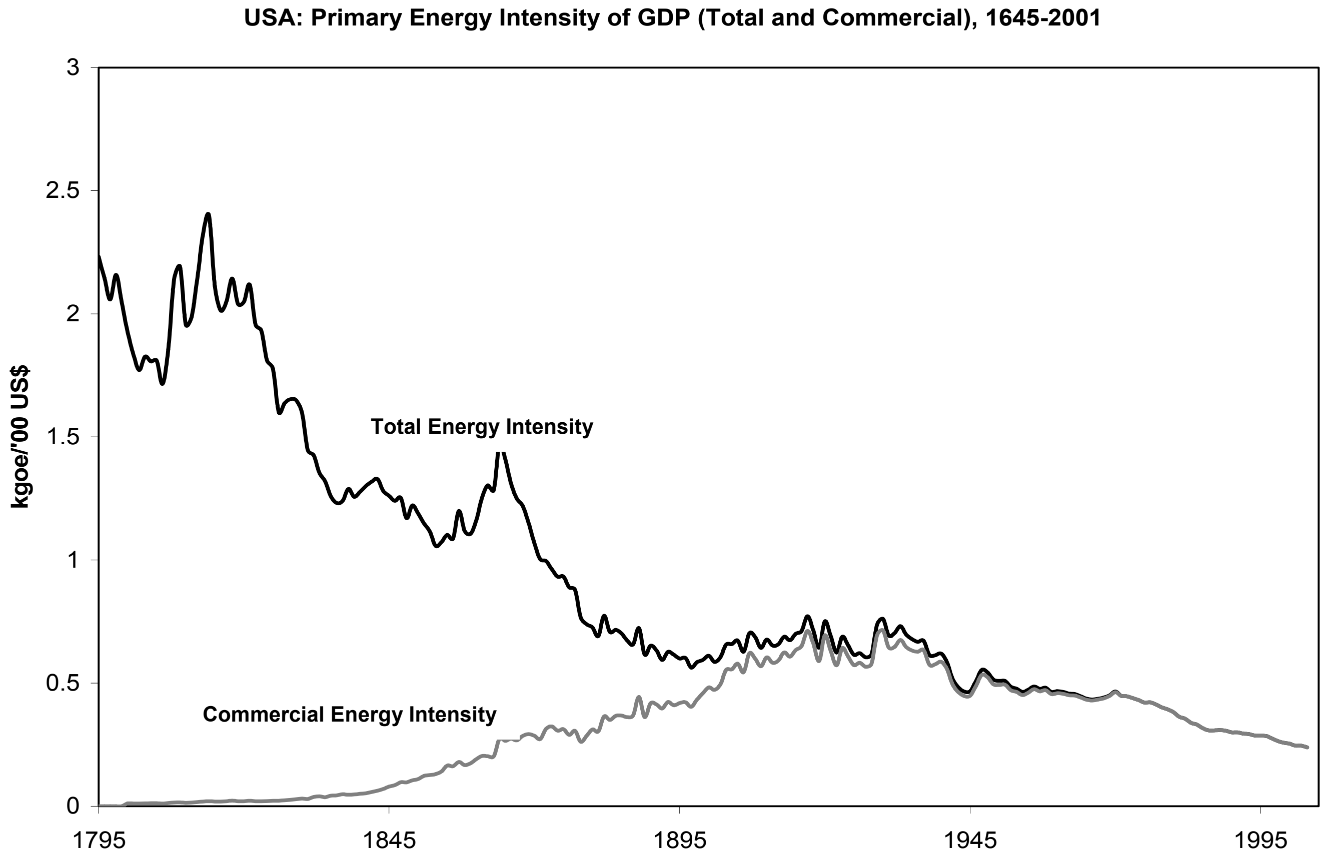

Figure 4: Total versus commercial energy intensity. While total energy intensity follows a continuous declining trend, commercial energy intensity proceeds along the path of an inverse-U. At very low levels of economic development commercial energy consumption is virtually nonexistent; commercial energy intensity is zero. Commercial energy intensity rises with industrialization and then falls as more energy efficient technologies enter the market. *Source: adapted from: Historical Statistics of the United States: From Colonial Times to the Present; IEA Energy Statistics, 1970-2002; Energy Information Administration (EIA), annual data; Mitchell, 1998; Maddison, 2001.*

While time series data indicates continuous improvements in aggregate energy intensity (including traditional energy sources) as income rises, commercial energy intensity follows a different path (see Figure 4). At low levels of economic development, commercial energy use is negligible; thus, commercial energy intensity approaches zero. During the maximum period of industrial commodity production, commercial energy intensities should rise, then fall with post-industrialization (Nakićenović et al., 1998). This "inverted-U" prediction is rooted in patterns of industrial activity, notably identified by Simon Kuznets (1955). Similar patterns are evident in many other economic activities linked to natural resources, such as local air pollution, where intensity declines at high incomes due to the lesser material intensity of a service economy, greater political demand for a clean environment, and the ability to outsource pollution through trade with material-intensive industrial exporters (see, for example, Grossman and Kruger, 1995; Frankel and Rose, 2002; Harbaugh et al., 2002; Stern, 2004). These patterns are often called "environmental Kuznets curves," and similar patterns suggest the existence of energy Kuznets curves.

While energy and economic growth have historically enjoyed close correlation, causation is harder to pinpoint. Many studies have sought to answer the question of causality at the national level. Some studies find that economic growth precedes increases in per capita energy consumption (Kraft and Kraft, 1978; Cheng and Lai, 1997; Ghosh, 2002; Jumbe, 2004). Others show that consumption of energy—in particular electricity—causes, or at least accelerates, economic growth (Shiu and Lam, 2004; Masih and Masih, 1996; Morimoto and Hope, 2004). Another camp finds bidirectional causality between the two (Asafu-Adjaye, 2000; Hwang and Gum, 1992). Finally, a number of studies find no statistically significant causal relationship (Akarca and Long, 1980; Erol and Yu, 1987; Yu and Choi, 1985; Yu and Hwang, 1984). Three factors appear to explain the variation in findings. First, the methods used to evaluate causation vary across studies. Second, some studies suggest causality solely for the short term, while others also focus on the longer term. Finally, exogenous events—notably, skyrocketing energy prices following the 1973 oil embargo—are likely to cause significant changes in energy consumption patterns, irrespective of changes in national incomes; yet most studies do not control for such episodes.

Such studies are only partly relevant to explaining the energy transition, which is marked not only by a rise in consumption of useful energy but also, more importantly, by a shift in energy sources and technologies. Quantitative macro-level studies examining correlation and causation between income and energy use often lump all energy carriers together and report income-energy relationships in terms of aggregate fuel use. Few studies have sought to rectify this problem; those that do find that income is the most accurate predictor of the energy transition (Pachuari, 2004; Leiwen and O'Neill, 2003). However, no literature has yet emerged around a consistent definition of the concept of an energy transition and thus, not surprisingly, causal analysis remains quite scattered.

4. ENERGY USE AND ECONOMIC DEVELOPMENT: MICRO PATTERNS

While many studies explore the income-energy link at the national level, micro studies exploring such linkages are scarce. Micro trends cannot be accurately extrapolated from national statistics. Especially for the poorest households, micro patterns can be obscured by larger industrial patterns that dominate national statistics. "Income" among the poorest segment of the population, particularly in rural regions of developing countries, is largely non-monetary. Such statistics are notoriously difficult to collect and rarely included in national energy statistics, mainly because self-gathering and informal trading of fuels leaves no record of transaction or taxation. Due to the absence of income data, many studies linking household income to energy consumption use expenditure as a proxy for income. While income and expenditure indeed tend to move in the same direction, correlation between the two is far from perfect. For example, a survey of rural Chinese households by Leiwen and O'Neill (2003) found the correlation coefficient (R^2) between income and expenditure to be only 0.516.[9] Furthermore, due to the difficulties in approximating energy use in rural areas, most micro surveys are carried out in urban areas where electric power is widespread—and thus considerable attention has been devoted to the particular issues surrounding estimation of the demand for electricity; electric power consumption is, in principle, easily estimated using power logs supplied by electricity distributors. Studies show that as income increases electricity consumption also increases, but at a less than proportional rate; income elasticity of demand for electricity is positive, but is less than one (Filippini and Pachuari, 2004; Tiwari, 2000). Mindful of such difficulties, we now summarize the major findings in the literature on observed trends in household energy use patterns.

(a) Aggregate Energy Use

Studies generally find that total final energy used in households increases with income—the household demands and is able to obtain larger quantities of useful energy. Gross energy consumption, also known as primary energy consumption, appears to proceed along the path of an inverse-U. The ability to afford more efficient technologies can yield lower primary energy consumption even as demand for end use energy rises. Moreover, at low income levels, a sizable slice of any increase in income goes towards the purchase of energy services to fulfill basic needs and wants (eg., cooking, heat, illumination). As incomes rise and basic energy needs are met, a smaller fraction of any additional income is allocated to the purchase of energy; income is instead diverted to entertainment and other services (Judson et al., 1999; Tiwari, 2000; Dube, 2003). In the Indian city of Hyderabad, for example, energy expenditures accounted for 15.4% of monthly income among households in the poorest income decile in 1999, but only 3.7% of monthly income among the wealthiest 10% of the population, even though *absolute* energy expenditure increased with income (ESMAP, 1999). Few studies have sought to empirically test the prediction of an inverted-U for energy consumption at the household level, but a study by Foster et al. (2000) found the prediction valid for Guatemala.

(b) Fuel Choice

Income growth is associated with an increasing role for modern energy sources—a pattern especially evident in a declining share of biomass energy (ESMAP, 2000; Victor and Victor, 2002; Ferguson et al., 2000; Reddy, 2003). In Brazil, for example, fuelwood accounts for almost all energy at the lowest income levels; more efficient liquid fuels comprise the majority of fuel consumption among the wealthiest residents (de Almeida and de Oliveira, 1995) (see Figure 5).

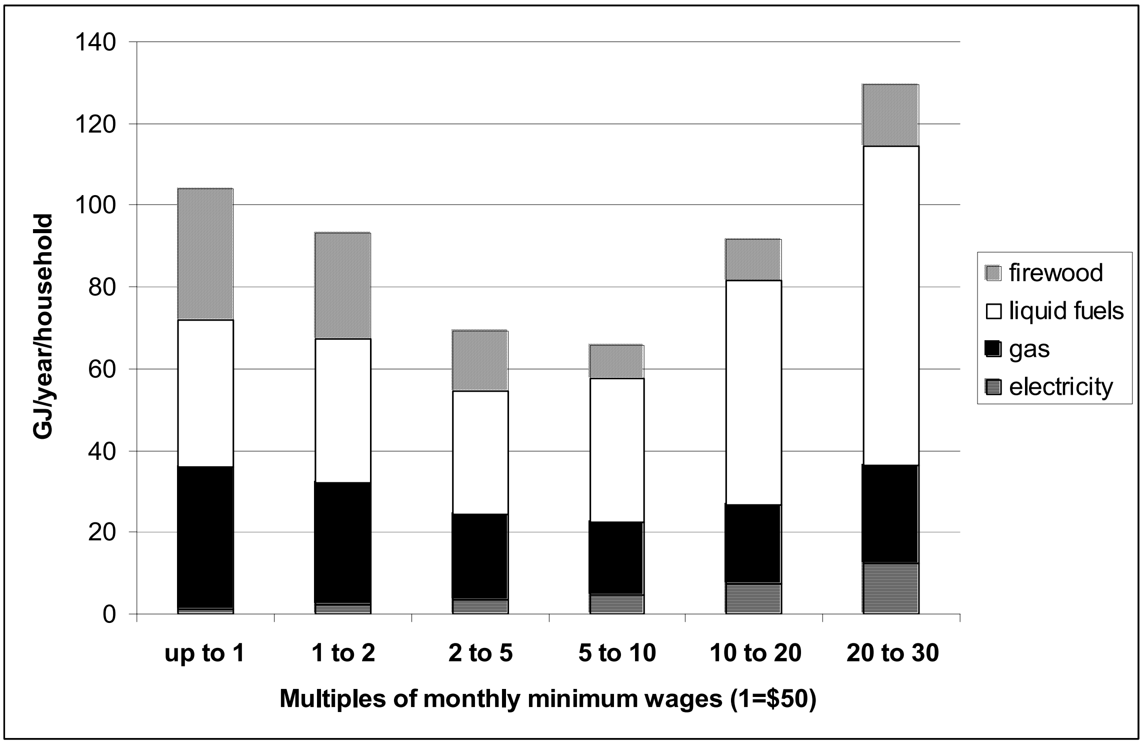

Figure 5: Brazil, 1988. Fuel use as a function of income (1988 US$). With rising incomes, a greater share of total energy is supplied by modern energy carriers. The marked increase in liquid fuel use in the highest quintile is likely due to the ability of the most wealthy to purchase automobiles for transport. *Source: adapted and redrawn from de Almeida and de Oliveria, 1995.*

(c) Energy Conversion Technologies

Energy conversion technologies, too, play a central role in the energy transition. When cooking, for example, traditional three-stone fuelwood stoves have an average efficiency of only 12-18%, while kerosene cookstoves have an average efficiency of 48%, and LPG stoves 60% (Jochem, 2000). For lighting, compact florescent lamps (CFLs) use 66% less energy than standard incandescents per kWh and last up to ten times as long.[10]

Although modern energy technologies are more efficient and less polluting than their traditional counterparts, high upfront capital costs and lack of infrastructure for the transport and distribution of modern energies often prevent low-income families from adopting such energy sources. CFLs, for example, occupy only a small market share, even in developed countries, due to their high initial cost.

One type of technology that has attracted considerable attention for its ability to provide low-income households with cleaner, more efficient energy is improved biomass cookstoves. Public policies aimed at introducing more efficient biomass-burning stoves emerged largely in response to the perceived "woodfuel gap" crisis of the 1970s, in which shrinking stocks of forests were seen as a consequence of residential fuelwood consumption. It was subsequently demonstrated that expanding croplands, not household energy demand, accounts for the majority of felling of forests; moreover, the woodfuel crisis appears not to be as widespread as originally thought—mainly because wood users tend to rely on sustainably grown sources (Leach and Fairhead, 2000). Subsequent studies showing the health burden of emissions from traditional cooking devices (e.g., open fires) and the toll that biomass collection takes on women's time, expanded the justification for improved stove programs (WEC/FAO, 1999; Leach and Mearns, 1988). More efficient stoves require less fuel, decrease cooking time, and alleviate adverse health impacts associated with burning biomass.

Several hundred stove research and dissemination programs have been undertaken in the past 25 years, primary in Asia and Latin America, and they range in scale from small and local to national programs that target over 100 million households (for a discussion of large-scale stove dissemination programs in India, see Kishore and Ramana, 2002; for Guatemala, see McCracken and Smith, 1998 and Boy et al., 2000).[11]

The Chinese National Improved Cookstove Program (CNISP), widely considered the most successful stove program to date, disseminated stoves to an estimated 185 million rural households—approximately 90% of all rural residences in China—between 1982 and 1998 (Smith et al., 1994). The improved stoves achieved, on average, efficiencies of 20-30%, compared to a maximum of 10% for traditional stoves. However, improvements in thermal efficiency can come at the cost of higher emissions (Edwards et al., 2004).

5. FACTORS OTHER THAN INCOME: PATTERNS AND CAUSATION

While income indeed appears to be the dominant force, the energy transition is not moved by money alone. A number of geographic and demographic factors, too, are linked with patterns of energy use and help to explain the shift to modern energy sources. In contrast to the confusion surrounding the causal linkages between energy and income, the literature generally concludes that a number of non-income variables are central to explaining observed patterns of energy use.

(a) Climate
Populations living in colder climates tend to consume more energy than those in warmer regions (Eberhard and Van Horen, 1995). This is especially true at lower income levels, where energy is often used to supply heating services; only at high income levels do households purchase fans and air conditioners that fulfill the demand for cooling (ESMAP, 1999). In rural China, for example, energy use is, on average, greater in cooler regions of the north than in warmer regions of the south (Leiwen and O'Neill, 2003).

(b) Resource Endowments
The relative shares of different fuels in a country's overall energy mix are determined in large part by a nation's endowment of natural resources and agricultural activity—especially at low income levels where non-native, imported fuels are beyond the economic reach of most (Kaul and Liu, 1992; Dunkerley and Gottlieb, 1987).

Where forest blankets a sizeable section of a country's total land area, such as in Laos and Cambodia, fuelwood is likely to account for a large fraction of total energy supply (Victor and Victor, 2002). Within countries, too, families living in close proximity to forests see a larger fraction of their energy mix comprised of woodfuel than do those located further from forested areas. A study conducted in rural India by Bowonder et al. (1985) found this pattern to hold true even for high income households.

Other countries lack large fuelwood supplies but boast an abundance of other primary energy sources. In South Africa, coal dominates domestic energy supply in coal-rich parts of the nation (e.g., around Johannesburg).[12]

(c) Distance to Markets
Rural towns and villages are particularly prone to a lack of modern energy services because of the high cost of connecting to energy infrastructures (eg., electricity grids) and service networks (e.g., kerosene and LPG supply chains). Even when remote regions are supplied with modern fuels, services to sustain energy infrastructure are often in short supply, making the availability of energy unreliable (ESMAP, 2002; Chaurey et al., 2004). Even high income households in remote areas are frequently forced to rely largely on biomass because the low density of demand for modern energy services makes the supply networks prohibitively costly (WEC/FAO, 1999). The trend of continued reliance on biomass fuels can be seen in India, where the top expenditure decile in rural areas uses almost seven times as much biomass energy as the top expenditure decile in urban areas (Pachuari, 2004).

In 2000, the percentage of urban areas with access to electricity stood at 91% worldwide, yet this figure was just 57% for rural regions due to the difficulties associated with rural electrification (IEA, 2002). And this figure may be overstated; China's rapid progress with rural electrification beginning in the early 1970s brought electricity to approximately 91%

of rural households by the year 2000, skewing the rural electrification rate upward (ESMAP, 2000).

6. IMPLICATIONS FOR HUMAN WELFARE

Modern fuels and energy technologies can bring a wealth of benefits for human health, economic status and education. Again, however, the frontier of research involves establishing exact cause-and-effect relationships. In this section, we review what studies have shown about the effects of the energy transition on health, time and income.

(a) Health

Indoor air pollution poses one of the greatest threats to health among the poor in developing countries and is due mainly to the widespread use of highly-polluting biomass fuels and technologies, such as poorly-ventilated woodfuel cookstoves. The World Health Organization (WHO, 2002) estimates that, worldwide, indoor air pollution is the second largest environmental health risk (behind unsafe water/sanitation), responsible for approximately 2.7% of the total Global Burden of Disease (GBD) (see Figure 6) (WHO, 2002; Smith and Mehta, 2003).

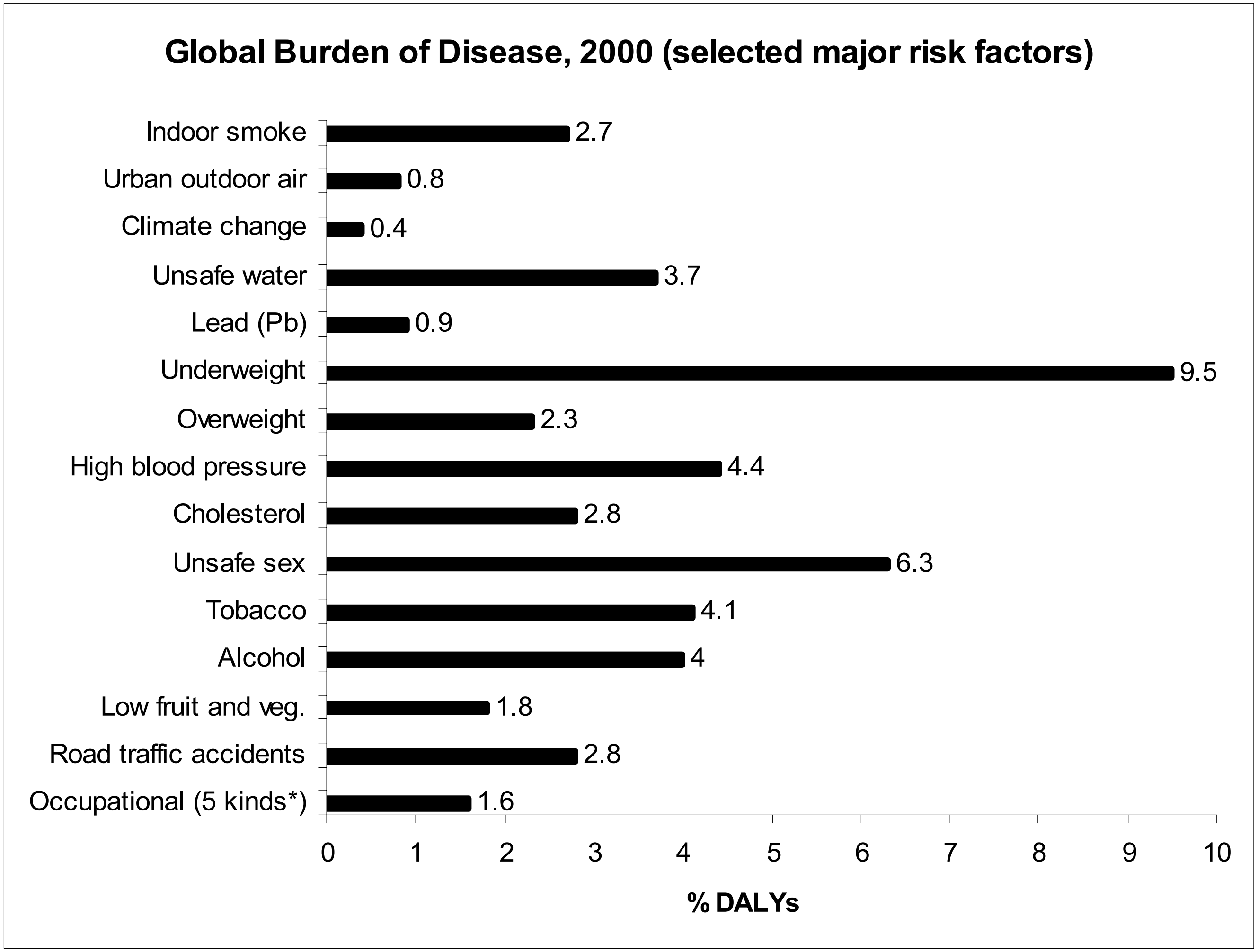

Figure 6: One measure of the health impact of indoor air pollution is reflected in the Global Burden of Disease (GBD), published by the World Health Organization (WHO). The GBD uses "disability adjusted life years" (DALYs) as measure of health impact. DALYs indicators are calculated by combining the number of years lost from premature mortality plus the number of years lived with disability. *Includes work-related: injuries; carcinogens; selected airborne particulates; ergonomic stressors; and noise. *Source: WHO World Health Report, 2002*.

Biomass stoves that burn wood, dung and agricultural residues emit large amounts of respirable particulate matter and trace gases such as carbon monoxide and nitrous and sulphur oxides (WHO, 2002).[13] Small particles of pollutant matter are able to enter deep into the lungs where they have the most damaging effects on health. The literature focuses on two classes of small particles that pose the greatest threat to human health: PM_{10} (particles with a diameter of 10 microns or less) and $PM_{2.5}$ (particles with a diameter of 2.5 microns or less). $PM_{2.5}$ is a subset of PM_{10}. There exists no internationally recognized standard for indoor air pollutant concentrations (Smith et al., 2000).

Women and young children—who are often carried on their mother's back—bear the brunt of the health burden, as they spend the most time in close proximity to polluting cooking and heating devices (World Bank, 1996; Naeher et al., 2000).[14] According to WHO estimates, indoor emissions from biomass stoves are responsible for the premature death of 2.5 million women and young children each year, in addition to contributing significantly to a large set of serious illnesses (IEA, 2002).

Susceptibility to harm from indoor air pollutants is elevated because emission levels are at their highest at the precise place and point in time that people are present: during cooking and meal times (Smith et al., 1994). Emissions from biomass-burning devices have been associated with such adverse health effects as asthma, chronic obstructive lung disease in adults and acute respiratory infections (ARI) in children (Smith et al., 2000) as well as birth defects and developmental problems (WHO, 2002).[15] And evidence is emerging linking high levels of ambient air pollution to tuberculosis, perinatal mortality (stillbirths and deaths in the first week of life), low birth weight, cataracts and other serious health problems (WHO, 2002). The introduction of modern energy and more efficient energy technologies results in a decrease in the incidence of death and disability caused by household air pollutants. Among other things, electricity enables refrigeration, which reduces the incidence of food-borne disease, and allows medical clinics to safely store medicines and sterilize instruments (WEC/FAO, 1999).

(b) Safety

A number of other health and safety risks are also associated with reliance on traditional energy use. In rural areas of the developing world, women and children walk long distances carrying heavy loads of fuelwood which can result in falls and fractures (WHO, 2000; Holdren and Smith, 2000). And traveling further from the home increases the risk of bites and stings from animals often found deeper in the forest or other vegetated areas (Holdren and Smith, 2000).

Physical safety is also a concern with respect to the direct dangers associated with lower end fuels, especially where children are concerned. Kerosene, often stored in old beverage containers, is frequently ingested by small children (Howells et al., 2003; ESMAP, 2003). In South Africa, where kerosene is an important fuel for many unelectrified households, kerosene poisoning is estimated to afflict at least 10,000 children annually (Eberhard and Van Horen, 1995).[16]

(c) Time budgets, labor productivity and income

While the relationship between energy use and human health has been relatively easy to observe, the link between energy choices and income has proved more difficult to establish. One area that has attracted attention is the change in household time budgets. The toll that traditional energy use takes on time budgets can be substantial, particularly for women. For those without access to modern energy supplies, a significant segment of each day's productive hours is dedicated to gathering biomass fuels. As woodfuel is used up and local supplies become scarce, families must travel further from home to gather wood (Bhatt and Sachan, 2004). In parts of India, between two and seven hours each day can be spent collecting fuels for cooking (IEA, 2002). In rural South Africa, the median time devoted to collecting woodfuel is approximately 6 hours per week. And in Nepal the median weekly time allotment is 7.5 hours (ESMAP, 2003). In addition to collecting biomass for fuel, households lacking electricity for pumping water often spend hours collecting water for cooking, personal consumption and irrigation (Saghir, 2004; World Bank, 1996).

The entrance of more modern, efficient fuels can, in principle, free time for more productive purposes such as education and commerce. What once took many hours of manual labor can be accomplished much faster with the motive power of machines. A study of households on the Indian island of Sagar Dweep found that the use of electric power (provided by a local photovoltaic, PV, plant) saved women an average of 1.5 cooking hours per day (Chakrabarti and Chakrabarti, 2002).[17] This results in both increased output of goods that can (potentially) be marketed and increased time for individuals to engage in other income-generating activities. Grain processing, beer brewing, blacksmithing and baking are among the small-scale enterprises enabled by the advent of electricity (WEC/FAO, 1999; Bastakoti, 2003). And modern fuels, especially electricity, provide illumination that extends the workday, again augmenting the ability to increase output. In villages in Namibia, for example, electrified stores are open longer hours and, on average, spend less on energy (primarily lighting and refrigeration) than those lacking electricity (James et al., 1999). And in Mali, the provision of electric power allowed women on one community to increase their production of shea butter from 3kg to 10kg per day; in another community, electricity increased the output of shea butter between 35-45% (UNDP, 2004).

However, modern energy alone does not guarantee economic benefits to households. Studies on the productive effects of supplying energy services have been liberal in listing the possible benefits, yet detailed studies that have actually demonstrated a cause-effect relationship between modern energy systems and sustained economic growth are few. Particularly in rural areas where economic and educational opportunities are lacking, time freed from labor-intensive tasks does not guarantee increased opportunities for education and income generation.

(d) Distribution of Impacts: Gender & Age

Modern fuel and technology—hallmarks of the modern energy transition—disproportionately benefit women, because it is women who shoulder the heavy burden of household tasks. Female children, for example, are frequently kept at home to help, rather than attending school like their brothers. Literacy rates among women in developing countries are 30% lower than those of men, and primary school enrollment for females lags 13% behind male enrollment; the gap is even greater at higher education levels. Over 70% of all people living on less than one dollar per day are women (UNDP, 2001).

The presence of electricity in the home greatly increases the probability that a woman will read (Saghir, 2004). First, electricity frees time from labor-intensive tasks—time which can be devoted to improving literacy. Second, kerosene and electricity (among other fuels) provide illumination into the night, extending the hours available for reading and other educational endeavors.[18] The above-cited study in Sagar Dweep found that electric lighting increased the average nightly study time of students by 2.25 hours (Chakrabarti and Chakrabarti 2002). And a separate survey of women in rural India shows that, while the literacy rate of wealthier women is higher than that of poorer women irrespective of their access to electricity, electricity access and time spent reading are highly correlated regardless of income class (ESMAP, 2004).

7. ENERGY POLICIES FOR THE POOR

Many societies have created a "social contract" around energy services such as electricity. The industry is organized to supply profit, but also to extend the benefits of reliable power to the citizenry (Heller et al., 2003). In the U.S., for example, the government established the Tennessee Valley Authority (TVA) following the Great Depression to (among other things) provide the low-income region of the Tennessee Valley with electric power at rates far below the national average (Roberts and Bluhm, 1980). And the inauguration of the Rural Electricity Administration (REA) in 1936 expanded the availability of low-cost electric power to American farms (Brown, 1980).

Today, numerous policies are advanced worldwide with the aim of alleviating energy poverty for the 1.6 billion people who still lack access to electric power. Yet extension of the grid does not ensure that households have access to electricity. The costs of grid connection, internal wiring and electricity end-use equipment are high, often beyond the reach of a large segment of the population. In India, high costs keep over 50% of households from connecting to the grid (IEA, 2002), even though upwards of 80% of villages have grid access (WEC/FAO, 1999). Those households that are able to afford electric power often face long wait times to be connected.

Even when households gain access to electricity, unreliable power supplies can impede success with electrification. Especially in relatively remote villages, grid failures frequently go unaddressed for long periods of time due to a lack of qualified support personnel. In a survey of Indian farmers, 80% classified electricity service as "irregular," and nearly half suffered from daily power losses (ESMAP, 2002).

Many rural areas remain isolated from the grid entirely. In these remote regions—where grid connection often appears an unlikely option in the near-term—LPG, kerosene, diesel and gas generators, dry-cell and car batteries and renewables are often advanced as a viable alternative to supply limited amounts of energy to households (Saghir, 2004; World Bank, 1996). Renewable energy resources are widely seen as socially and environmentally attractive; emissions of harmful pollutants are greatly reduced and the "footprint" left by energy-generating infrastructure is often smaller than in the case of conventional energy technologies. On the village level, micro-hydro mini-grids supply more electricity than any other form of renewable power—over 50 million households are served by such small-scale hydro schemes (Martinot et al., 2002). For individual households, renewable energy has so far been promoted predominantly with respect to photovoltaic (PV) technologies (Martinot et al., 2002). PV's promise, particularly for the rural poor, lies largely in the ability to deploy solar on a small scale (relative to that of other renewables), as well as in solar energy's abundance relative to the low power requirements of typical rural users. While the environmental and social benefits of renewables have become widely evident, they remain more expensive per unit of power than fossil fuels. Renewable energy resources (excluding large hydro) currently supply 17.6% of global primary energy production (IEA, 2004).[19] The costs of renewable energy systems are falling as manufacturing techniques and technologies advance through experience, yet they are still substantially higher per unit of energy supplied than those of most conventional energies.[20]

At market rates, modern fuels are often beyond the reach of the poorest households. Many modern fuels—such as LPG—can only be purchased in large, "lumpy" quantities which cost more than most low-income households can afford. In Guatemala, for example, butane is rarely adopted by any but the wealthiest families largely because it is sold only in large quantities—35-lb. cylinders—which cost approximately US$9 each (Foster et al., 2000).[21] In contrast, energy carriers such as kerosene or woodfuel can be purchased in small, discrete bundles. In South Africa, this partly explains why kerosene is more readily adopted than LPG, even though the latter is cleaner and safer (Howells et al., 2003).

In an effort to overcome obstacles to modern fuel use, governments often subsidize fuel prices. In principle, subsidies increase the ability of the poor to access energy services. Yet in practice, policies intended to increase poor people's access to electricity and other modern fuels and energy technologies often disproportionately increase energy access for middle and upper class consumers who have greater energy demand (Saghir, 2004; World Bank, 1996; Barnes and Floor, 1996; Pitt, 1985). In the Indian city of Hyderabad, a 1994 study showed that the highest income decile received an average aggregate fuel subsidy of 153 Rs/month, while the lowest decile received an average subsidy of only 64 Rs/month (although the subsidy directed to the lowest decile was equal to approximately 29% of income, while it was only 10% for the wealthiest decile) (ESMAP, 1999).

Where energy sources are highly subsidized and appropriate price signals are absent, people are prone to profligate energy use since they bear little of the true cost of supplying such services (Foley, 1992). And subsidies can constitute a major financial drain on local utilities, leaving them unable to finance further extensions in energy infrastructure—such as in India where all the state-owned electricity utilities are technically bankrupt, mainly due to ultra-low, subsidized prices charged for power supplied to farmers (Tongia, 2004).

However, some subsidy schemes have been successful. Once-off subsidies, directed at alleviating some of the initial capital cost of new fuels and technologies, are more effective and sustainable than those that reduce recurrent operating costs. The initial cost of acquiring a new fuel source often constitutes the biggest barrier to modern energy adoption (Foley, 1992). Continued subsidy produces ongoing distortions that can greatly increase the cost of the program. Many countries set "basic" or "lifeline" tariffs that provide the poor with low levels of energy at very low cost (or free)—these are also promoted as a way to provide the poor with power to meet their most basic needs while minimizing the benefits that accrue to the better off (ESMAP, 2000). The level of such subsidies must be set appropriately, however. In Yemen, for example, the excessive electricity "lifeline" rate of 200 kWh/month meant even relatively wealthy households reaped the benefits of the subsidy (Barnes and Halpern, 2000).

Over the past two decades, interest has gradually shifted from subsidies to making a market for energy supplies. This move reflects a realization on the part of policy makers of the often excessive cost of subsidies, as well as growing global patterns of economic reorganization that tend towards more market-based systems. Electricity markets in developing countries are becoming increasingly liberalized with a host of private players entering into the business of generation and distribution. Furthermore, there is a growing recognition that efforts at energization will fail unless a sustainable business model is created.

In Kenya, decentralized electric power systems have come to supply more electric power than the grid, despite the fact that consumers get no subsidy and units are sold on a cash basis (WEC/FAO, 1999; Hankins, 2000). And in the Gansu Province of northwestern China, upwards of 10,000 solar home systems have been sold on a commercial basis (Lew, 1998). In other regions of China, as well as in the private energy markets of Kenya and Morocco, distributors have found that the scaling the size of the systems to a level that households could afford both eliminated the need for subsidies and encouraged energy conservation (Martinot et al., 2002).

Another well-functioning market in China is the CNISP, China's cookstove program (discussed earlier), which achieved adoption rates unsurpassed by any other national stove scheme despite the fact that the share of the cost borne by the state under the CNISP was small (only about 15% of the overall program cost) (Smith et al., 1993). That households shouldered much of the cost likely increased the likelihood of using the stoves and maintaining them in good working condition. In contrast, India's National Program on Improved Chulas (NPIC)—the only other improved stove program large enough to compare to the CNISP—supplied a direct cash subsidy that amounted to 50-75% of the total program cost (Kishore and Ramana, 2002; Kammen, 1995). The outcome of that program was far less favorable, with many stoves left lying around unused or falling apart for lack of care and maintenance, which is in most cases not locally available (Neudoerffer et al., 2001; Kishore and Ramana, 2002). Faced with limited capital to finance the expansion of energy infrastructure, coupled with the mounting evidence of the superior efficiency of market mechanisms, governments may increasingly turn to the private sector to provide energy for the poor.

7. CONCLUSIONS

The modern energy transition is associated with changing patterns of energy production and consumption and rising standards of human welfare worldwide. Yet the pace and pattern of the transition is highly uneven across world regions. The effects of the energy transition—improved health, increased literacy and the freeing of time for entertainment and economic improvement—are highly visible and thus readily reported, yet the factors that cause the transition are more murky. We have reviewed the socio-economic and demographic factors (income, urbanization and education, among others) that appear to accompany the shift to more efficient fuels and technologies, yet concrete conclusions about causation are more difficult to decipher.

The absence of quantitative micro-level studies presents one of the biggest barriers to coming to conclusions about how and why the transition takes place and its effects on welfare. The sample of studies aimed at assessing the drivers of the energy transition is expanding, yet the multiplicity of methods and models used, coupled with a lack of reliable data, makes critical comparisons difficult. Policies and programs are often advanced without an adequate understanding of the factors that influence household energy choices, and as a result they are misdirected and mismanaged.

Few would dispute that energy is critical to economic development. Yet, absent clear consensus about the causal relationship between energy and economic growth, it has proved difficult for governments to target pro-poor energy policies. Nor is it clear whether such policies attain the greatest leverage over poverty; perhaps policies that encourage broader economic development would be more effective than those that specifically target energy services.

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NOTES

[1] The Neolithic Revolution unfolded as a series of small changes over the course of at least a millennium, but the beginning of organized agriculture can be dated to about 8500 B.C. in Messopotamia; organized agriculture in other regions of the globe first appeared (independently) over the proceeding few millennia.

[2] Agriculture encouraged population growth for several reasons. First, the increased availability of nutrition allowed the population to expand. Second, increased settlement size was likely a response to the need for defense (Seabright, 2004). As people settled on agricultural plots and become less mobile—and with more resources to defend—people needed to be able to defend themselves from outside threats. As a settlement increases in size, it is better equipped to defend itself for two reasons: a) the ratio of its perimeter to its area shrinks; thus, less defensive walls are needed for every unit of land contained therein; and b) manpower is greater the larger the community size. Third, food harvesting and processing yield a greater per capita output if many people are working cooperatively (Hassan, 1979).

[3] An example of efficient energy use by industry was coke-fueled smelting of pig iron in blast furnaces, which consumed only one-tenth of the energy per mass of finished product than charcoal-based production. (Smil, 1994)

[4] Steam did not fully displace traditional forms of motive power (horse-drawn coaches and wind-powered sailboats) until about 1920 (Smil 1994).

[5] Petroleum production in 1900 was 8483 thousand metric tons and in 1990 was 371,032 thousand metric tons. Natural gas production in 1900 was 3625 million cubic meters, rising to 509,510 million cubic meters in 1990.

[6] Liquid or gaseous fuels are nearly always traded in commercial markets because they are not readily available and require processing that is beyond the means of households.

[7] On this point—the causes of the energy transition—we reflect the tenor of the literature. However, we note that there may be other reasons for the energy transition that, so far, have not attracted analysis. For example, households may acquire modern fuels and appliances simply because they are modern—these acquisitions are social signals that are not simply for the purpose of freeing time and cutting adverse health effects.

[8] It is important to note, however, that countries with the same GDP per capita often vary widely in their per capita energy consumption (Dunkerly and Gottlieb, 1987).

[9] The results arrived at by Leiwen and O'Neill suggest that expenditure is a better predictor of aggregate energy use and income a better predictor of a shift toward more efficient fuel types.

[10] These figures refer to the U.S. government's ENERGY STAR-qualified compact fluorescents. http://www.energystar.gov/index.cfm?c=cfls.pr_cfls

[11] There exist a myriad of specific stove models across countries; however, they can be generally grouped into 2 types: portable and fixed location. Some stoves are equipped with flues, or chimneys, to funnel emissions away from the source of combustion; others simply release pollutants into their immediate surrounds.

[12] In 2001, coal accounted for approximately 78% of South Africa's final energy consumption. The Department of Minerals and Energy, Republic of South Africa.

[13] Particulates are complex mixtures of chemicals in solid and liquid form; measured by diameter in millionths of a meter (microns), concentrations of particles are expressed as the weight of particles (in micrograms, mg) per cubic meter (m^3) of air (mg/m^3).

[14] In studies citing the effects of indoor air pollution, young children are typically classified as those under 5 years of age. Those above 5 years of age typically spend less time accompanying women during household cooking tasks.

[15] ARI affects people of all ages, but is most common in children and the elderly. In children under five years of age, three to five million deaths per year are attributable to ARI (75% of which are from pneumonia). ARI significantly effect lowers the average for productive life years (measured in disability adjusted life years, DALYs) due to the fact that it afflicts individuals at a very young age.

[16] Estimates of paraffin poisoning in South Africa vary significantly. The 10,000 figure represents a relatively conservative estimate and is based on Eberhard and Van Horen 1995.

[17] While PV is rarely used for cooking at low income levels, this example serves to illustrate the time-savings that can be realized from electric power.

[18] One often-overlooked factor, however, is quality of lighting. Often, the illumination provided by low-wattage electricity is not sufficient to read by.

[19] Data for 2002. Includes solar, geothermal, wind, heat, combustibles and waste.

[20] In the U.S., the cost of PV modules declined from approximately $30/W in 1975 to under $5/W in 1998 (U.S. Department of Energy).

[21] The cost of a butane stove itself (about US$200) is also an obstacle to adoption.