Poverty, Energy, and Resource Use in Developing Countries

Focus on Africa

Daniel M. Kammen[a,b,c] **and Charles Kirubi**[a]

[a]*Energy and Resources Group, University of California, Berkeley, California, USA*

[b]*Goldman School of Public Policy, University of California, Berkeley, California, USA*

[c]*Renewable and Appropriate Energy Laboratory, University of California, Berkeley, California, USA*

Energy poverty affects poor communities and poor nations far more severely, and more directly, than in developed nations. Poor rural communities are particularly vulnerable, and the poor globally spend by far the largest percentage of income on energy. To make matters worse, record-high oil prices combined with sharp decline in foreign exchange earnings are key processes influencing the energy sector in Africa. These increases cause tremendous local hardships, but can be used to steer development decisions toward renewable energy technologies. At the same time, breaking up of public monopolies and liberalizing generation and distribution provides an opportunity for a new approach to rural electrification. Given the right incentives and institutional framework, a new set of players (e.g., private entrepreneurs, cooperatives, nongovernmental organizations, and communities) are likely to emerge and dominate reformed rural electricity markets in the future. Through technological and institutional "leap-frogging," Africa stands to gain significantly by augmenting current initiatives with experience and lessons recently gained in South Asia and Latin America. In these regions, a number of remarkable recent strides to seed and grow rural electricity markets while stimulating and encouraging private investments. Examples of innovative regulatory tools to address poverty include licensing, standards and guidelines, metering, tariffs, transmission charges, and performance-based contracting for energy services.

Key words: **Africa; poverty; renewable energy; rural electrification**

Introduction

Sub-Saharan Africa (SSA), the region with the highest levels of the population in poverty, also has the least access to modern supplies of commercial energy. Since the late 1980s, the absolute number of the poor in SSA has grown five times more than in Latin America and twice that in South Asia.[1] In the past decade, SSA has lagged behind globally not only in gross domestic product per capita but also in electricity consumption. The levels of electricity consumption are strikingly low at 126 kWh per capita, or 150 times that in industrialized countries.[1] Further, in the 1990s, the average per capita consumption of modern energy in Africa was less than 300 kg of oil equivalent, or approximately 50% of the global average.

After five decades of rural electrification, less than 5% of the rural population has access to the central grid in SSA, and new connections barely keep pace with population growth (Table 1). The patterns of regional energy production and consumption are far from uniform, however. North Africa is heavily dependent on oil and gas and the Republic of South Africa, on coal and nuclear power; in the rest of SSA, biomass (charcoal, fuelwood, dung, and crop residues) supplies 70%–90% of energy demand. The Republic of South Africa accounts for 50% of installed electricity generation on the continent.[2] Moreover, energy use and energy investments SSA are clearly mismatched. Despite serving a minority, large-scale conventional energy sectors (electricity and petroleum) receive most energy invest-

Address for correspondence: Daniel M. Kammen, Energy and Resources Group, 310 Barrows Hall, Mail Code 3050, University of California, Berkeley, CA, 94720.
kammen@berkeley.edu

Ann. N.Y. Acad. Sci. 1136: 348–357 (2008).
doi: 10.1196/annals.1425.030

TABLE 1. Electrification rates in selected sub-Saharan African countries

Country	Total population below poverty line[a] (%)	Electricity use per capita (kWh)	Electrification level (%)			Traditional energy (% total energy consumption)
			Rural	Urban	National	
Malawi	54		<1	46	6	82
Ethiopia	76	24	<1	12	3	93
Eritrea		44	2		18	66
Mozambique	78	48	1	18	9	93
Sudan		49			31	
Benin		54			25	90
Tanzania	51	62	1	26	9	95
Congo		70			20	75
Nigeria		89			45	
D.R. Congo		90			8	
Angola		92			5	
Botswana	33		8		26	
Zimbabwe	41		19	80	41	60
Namibia			15			
Zambia	86		2	25	18	78
Uganda	55		1	20	4	92
Kenya	47	104	4	46	15	78
South Africa		3800	50	84	67	

Sources: World Bank[1]; AFREPREN/FWD[21]; Ministry of Energy, Kenya[22]. Entries with no data reflect either the lack of reported information or cases where published estimates differ significantly.

[a]Defined by national poverty references using PPP of $1/day.

ments. This is at the expense of the abundant, mature, and cost-effective small-scale renewable energy technologies, such as microhydro, solar energy, and improved biomass cookstoves. Many studies in SSA and elsewhere demonstrate strong empirical linkages between renewable energy technologies and a wide range of the United Nations Millennium Development Goals, including reduced child and maternal mortality, poverty alleviation, improved education, and health services.[3,4]

Innovative Regulatory Tools for Extending Rural Electrification in Africa

SSA, like many other least-developed countries, has spent more than a decade implementing a standard reform package[a] aimed at creating competitive markets in the power sector. Implementation of these reforms raised many hopes, not the least of which was increased access to rural electrification. After nearly two decades of implementation, the results are disappointing, however. Improvements in electricity access, quality, reliability, and affordability have not materialized as expected. Several international and national factors and processes underlie the failed promise of reforms in SSA. First, whereas reforms in Organisation for Economic Cooperation and Development (OECD) countries were limited to the power sector and supported by strong and functional economic and political systems, reforms in non-OECD countries, including SSA, were economy wide, overlaid on weak and dysfunctional economic and political institutions.[5] This situation led to mismatched expectations and capabilities in non-OECD countries. Also, although reforms improved financial and technical performance in certain utilities (e.g., in Tanzania), researchers have contested the international indicators (e.g., customer–employee and electricity sales–employee ratios) used to measure such success.[6] With the monopolistic power supply conditions in developing countries, employee performance has limited effect on customers' choice. Moreover, using consumption average to rate utility performance created negative incentives toward rural areas where demand is generally low and dispersed. The reforms also justified massive retrenchment and steep rises in tariffs, by as much as 300% in Ghana, for example, triggering social and political unrest.[5] By narrowly focusing on cost recovery and finance, the standardized

[a]Common elements of the package include the following: corporatization (e.g., separation of utility from ministry, engage private management); commercialization (cost recovery, reduce subsidies); create independent regulator; legalize independent power producers; restructuring (vertical and/or horizontal unbundling); privatization; competitive markets (single buyer, cost- or bid-based pool).

TABLE 2. Comparing the new rural electrification regime with the old system

Characteristic	Old regime	New regime
Provider	Large, vertically integrated, state-owned utility	Small, mostly private sector investor/ operators or community organizations
Networked	Grid connected	Off-grid[a]
Technology	Conventional	Mostly renewable
Scale	Large scale	Small scale
Funding	Government	Private sector, community or government
Demand	Low	Very low
Market	Monopoly	Competitive
Ability to pay	Low	Low
Generation cost per kWh	Low	High
Total cost	Very high	High but lower than grid extension
Motivation	Politically driven	Income generation driven

Source: USAID.[23]

[a]Off-grid implies unconnected to the national, high-voltage transmission grid. Many rural suppliers are developing or will develop small distribution minigrids.

reform menu lacked the appropriate breadth and sequence required to address important social and public goals, such as electrifying the poor—both urban and rural. Further, instead of lowering the cost of electricity supply, thus increasing demand, breaking up of public monopolies and liberalizing generation and distribution has had the opposite effect.

In the postreform period, rural energy service suppliers in Africa will be different from the large national utilities with which most governments are traditionally familiar. Given the right incentives and institutional framework, individual entrepreneurs, small companies and industries, nongovernmental organizations, church groups, farmers, and local communities are likely to catalyze and dominate the liberalized rural electricity markets in the future (TABLE 2). These players will be inexperienced with electricity and constrained by capital and technical skills. Though limited, available evidence suggests that deficiency in technical know-how and finances is more than made up for by profit motive, ability to manage costs, and collective action. The Urambo Electric Consumer's Cooperative in Tanzania is a promising example; it outperforms the national utility, Tanganyika Electricity Company (TANESCO), on many fronts: lower operation and maintenance costs, setting and enforcing affordable but cost-reflective tariffs, and improved customer service.[7]

In Latin America, South Asia, and recently SSA, the emerging rural electricity suppliers can be grouped in three broad models: concessions, cooperatives, and dealers. In the concession model, the entity or concessionaire is granted a franchise to supply power for a profit. Supply can take different forms: distribution or generation or generation and distribution. Also, concession can be either exclusive or nonexclusive. The former is time bound, with the concessionaire's enjoying exclusive right to supply to a predetermined geographic territory. Producing and/or distributing goods and services for its members, a cooperative is a commercial enterprise created to serve the interests of its members. Electric cooperatives pioneered rural electrification in the United States in the 1930s.[b] Dealers sell (and often) maintain energy equipment, such as solar photovoltaic (PV) cells, and related components to rural customers. Dealers face many challenges including stiff competition, limited cash flow, limited access to credit, and low purchasing power of rural customers. Successful models in Kenya and Sri Lanka have penetrated and grown through existing dealer networks, retail businesses, and personal relationships. These networks help in lowering the per-unit costs because many costs are spread over a wide range of retail products. Through cash sales and the checkoff system, the rural middle class, notably tea and coffee farmers and salaried government employees, such as teachers, have provided a critical market for solar PV in Kenya.

Africa stands to gain the most by drawing from vast experience and lessons gained in South Asia and Latin America on how to seed and grow rural electricity markets while protecting private investments. Several innovative regulatory tools have demonstrated success in these regions. Examples include licensing, standards and guidelines, metering, tariffs, and output-based contracting. Licensing is a standard regulatory tool for

[b]For details, see the National Rural Electric Cooperative Association (NRECA; http://www.nreca.org).

restricting access to an industry. Licensing can vary from a lengthy and costly bureaucratic nightmare to a simple one-step process. Generation and distribution in rural India is license free; rural generation and distribution below 1 MW and 0.5 MW is license exempt in Nepal and Uganda, respectively.[8,9]

Despite power sector reforms, conventional technical standards inherited or adopted from Europe and the United States are still enforced for rural electrification in most African countries. Seemingly small changes, such as reducing the size of poles and increasing the distance between poles (long span), can dramatically cut costs. In El Salvador, for example, the long span is 90 m as opposed to 135 m in many other countries.[10] Given the low loads in rural areas, switching from three-phase to single-phase transmission is economically sensible. Many rural towns in the United States, with much higher loads than many urban areas in Africa, continue to be served cost-effectively by single-phase power. Further, the Single Wire Earth Return systems are the cutting-edge technology for rural electrification in many countries, such as Australia, Canada, New Zealand, Brazil, India, Tunisia, Botswana, South Africa, and Namibia.[10]

Conventional metering is inappropriate for rural Africa for at least two reasons. The transaction and administration costs of installing and reading meters and bill preparation by far exceed the corresponding revenue generated because of low demand, subsidized tariffs, and scattered rural population. Also, unlike the large-scale utilities, distributed generation systems operated by rural electricity suppliers are likely to be too capacity constrained to meet temporary peak demands. This problem can be easily solved by metering on the basis of instantaneous power consumed (kilowatts) rather than cumulative consumption (kilowatt-hours). Customers are then charged for a preset maximum power per month, and circuit breakers, which are much cheaper than normal meters, are used to enforce load limits.

Getting tariffs right is essential if rural electricity markets are to emerge and grow in Africa. Common claims that rural people cannot afford the true cost of electricity can be misleading. Through wide use of batteries to power lights, television, and radio, a sizable proportion of rural people have demonstrated willingness and ability to pay for improved energy services on the order of US$3–$10/kWh. In setting tariffs, the regulator must therefore ensure that private rural electricity suppliers receive a reasonable return on investment. This is not an argument against subsidies, however. If directed at capital investments rather than operating costs, combined with cost-reflective tariffs, technology-neutral subsidies could make a positive difference in rural electrification.

Linking subsidies to concrete outputs is another institutional innovation suitable for the energy sector in Africa. Introducing supply competition through output-based contracting for rural electrification has increased electricity access while lowering costs in Cape Verde, Chile, and South Asia.[11] Under this system, private companies bid to supply rural electricity services to selected areas at lowest cost. Payment of subsidies and/or renewal of contracts (by government or donors) are conditional on meeting predetermined targets (e.g., number, rate, and cost of connections).[c] Active participation of the beneficiary community through financial or labor contributions, in local management, and in the contract renewal processes can lower costs further, enhance monitoring of targets, and improve service delivery.

Wheeling-and-dealing and net metering are other transmission constraints facing rural electricity suppliers. Despite two decades of reforms, transmission and pricing mechanisms and rules are heavily skewed in favor of utilities with steady and predictable flow of power. This situation presents a serious setback to rural suppliers that are operating and/or considering investing in highly variable renewable sources, such as solar, wind, microhydro, and cogeneration. Moreover, metering systems have not been adjusted to measure two-way flow. Consequently, rural industries (e.g., tea and sugar factories operating microhydro and cogeneration distributed generation, respectively) cannot sell electricity to the national grid when they have surplus generation while buying back during low-generation seasons. Another major disadvantage is the pricing of transmission services. Utilities charge a flat transmission fee irrespective of distance wheeled, congestion, and line losses incurred. Uniform transmission pricing fails to reward rural suppliers located closer to their demand centers for lowering line losses and cost of power supply vis-à-vis state-owned utilities.

The New Promise of Renewable Energy in Africa

In 1981, Africa hosted the first International Conference on New and Renewable Sources of Energy in Nairobi. As the world faced unprecedented high petroleum energy prices, Africa, as elsewhere in the

[c]This approach has been used to effectively deepen access to cellular telephony in countries, such as Kenya, Ghana, and Uganda.

TABLE 3. Dissemination of improved household woodstoves in sub-Saharan Africa

Country	No. of improved household stoves disseminated
Botswana	1500
Malawi	3700
Zimbabwe	20,880
Sudan	28,000
Ethiopia	45,000
Eritrea	50,000
Uganda	52,000
Tanzania	54,000
South Africa	1,250,000
Kenya	1,450,000
Total	2,955,080

Source: AFREPREN/FWD.[21]

world, embraced the strong optimism and vision for transition to renewable energy sources. Although important initiatives have since been taken, notably in biomass and solar energy, the promise of renewable energy in Africa remains largely unmet.

Biomass Energy and Cogeneration

The renewable energy conference played a key role in launching programs for research, design, and dissemination of improved household woodstoves in the region. Designed to improve both combustion and heat transfer efficiencies, about 3 million improved household woodstoves have been disseminated in more than 10 African countries (TABLE 3). Most of the improved stoves have been adopted in urban households, and therefore dissemination to rural areas needs to be aggressively pursued.

In 2001, 400,000 premature deaths, especially for women and children, in SSA, or 25% of such deaths globally, were attributable to indoor air pollution from biomass use. This mortality trend is projected to reach 10 million by 2030.[3,12] Rapid transitions to sustainable charcoal production and could prevent 3 million deaths, however. Moreover, biomass fuels, particularly the charcoal trade, are a vital source of livelihoods and employment to millions of people in Africa. In Kenya, for example, charcoal trade provides direct employment to about 200,000 people and supports roughly 2.5 million livelihoods, with women playing a significant role in production, distribution, and selling.[13]

In SSA, cogeneration provides substantial opportunities for producing electricity and/or process heat cost-effectively and in environmentally friendly manner. Various forms of biomass, notably sugar cane waste (bagasse), could be used. Sugar is a major agricultural export crop in many countries, such as Ethiopia, Madagascar, Malawi, Mozambique, Swaziland, Zambia, and Zimbabwe. Mauritius already meets 20% of its total electricity demand from bagasse-based cogeneration; estimates show that 16 other SSA countries could meet significant proportions of their current electricity demand through this process (TABLE 4).

Solar Energy

For lighting, rural households in Africa spend an overwhelming amount on kerosene, a fuel that delivers poor and costly lighting services. The cost per useful lighting energy services (dollars per lumen-hour of light) for kerosene lighting is 3000 times higher than that for compact fluorescent light.[14] This makes solar PV an increasingly important alternative for cleaner and cheaper lighting services. In addition to lighting services, demand for "connective power" by the rural middle class, that is, electricity to power television, radios, and cellular phones, is the key socioeconomic use driving the solar PV in rural Africa. In Kenya, solar electrification has outpaced grid connection, with cumulative sales of solar home systems in excess of 200,000 units and growing at 18% annually.[15]

Debates about solar PV in SSA revolve around cost, equitable access, and potential for productive uses to generate income and reduce poverty. Of primary concern is the high cost of the technology. The cost of a typical household PV system (40–50 W_p) can be as high as 200% of the gross national product (GNP) per capita of most SSA counties (TABLE 5). The PV cost estimates could even be higher considering that rural incomes are much lower than the national average GNP per capita in SSA. Through better-quality lighting, solar PV has enabled important but modest income generation activities in Africa. However, the amount of power delivered by typical solar home systems is insufficient for mechanical applications, such as agroprocessing, irrigation, welding, and carpentry. These productive uses account for more than half of off-farm income and employment in rural Africa.

The high costs combined with the market-driven dissemination approach have decidedly kept solar PV beyond the reach of most rural poor. The richest 10% own half of all solar PV systems in rural Africa. Another important observation is that the small-size PV systems affordable to rural middle class citizens deliver less than 1/10 of the electricity (about 30 kWh/year)[d] used by an average grid-connected rural household.

[d]For comparison, an average U.S. household consumes about 10,000 kWh per year—20 times more than grid-connected rural households and 250 times more than solar energy–using households in Africa.

TABLE 4. Current status of cogeneration in east and horn of Africa

Country	Total potential for cogeneration: energy (MW) 2001	Current cogeneration installed capacity (MW)	Current cogeneration installed installed capacity (% of total potential)
Tanzania	395	35	10
Kenya	350	37	10
Uganda	40	10	25
Ethiopia	430	13	3
Total for east and horn of Africa	1200	100	10

Source: AFREPREN.[24]

TABLE 5. GNP per capita and cost of household solar PV system

Country	GNP per capita	Estimated cost of solar PV system (40–50 W_p) US$	Estimated cost of solar PV system per GNP per capita (%)
Zambia	330	1200	364
Uganda	310	1037	335
Eritrea	200	600	300
Kenya	350	620	177
Lesotho	570	1000	175
Zimbabwe	610	800	131

Source: Karekezi and Kithyoma[8]; Jacobson and Kammen.[15]

Apart from delivering low-quality lighting at high cost, extensive fuel-based lighting in Africa is also a major source of greenhouse gases. Used 4 h a day, a typical kerosene lantern emits more than 100 kg of greenhouse gases into the atmosphere each year.[14] But rapid penetration of cost-competitive, cleaner alternatives, such as solar PV and solid-state white light-emitting diode, is constrained by substantial subsidies extended to kerosene and propane fuels by African governments. In addition to creating price distortions and encouraging fuel diversion and adulteration into the transport sector, fuel subsidies divert scarce public resources from critical pro-poor social services, such as education and health.

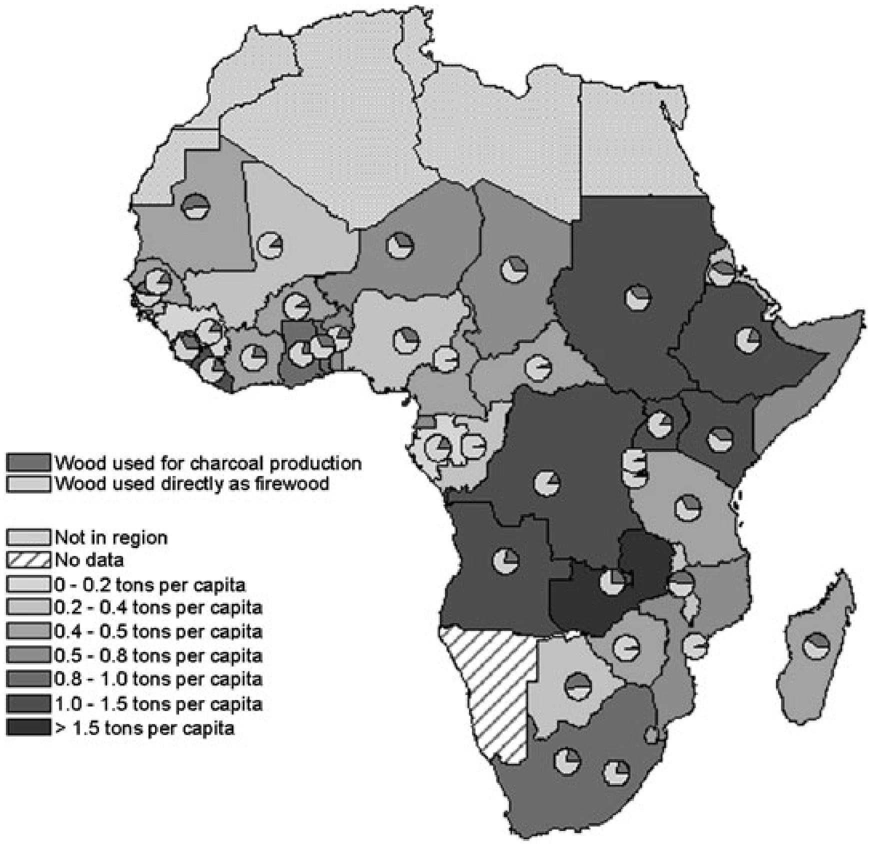
Heating Energy Services

Electrification commands the largest share of rural energy projects and funding in Africa, as in other developing countries. Although electricity is important for rural development, studies have shown that heating energy—which is too costly to provide with electricity—is crucial particularly for cooking and income generation. In many parts of SSA, women travel for 6–8 h a day collecting sparsely distributed fuelwood for their cooking needs. Heating energy is also crucial for many rural industries and microenterprises, such as beer brewing, brickmaking, and food processing. These enterprises are the primary sources of rural and urban livelihoods, particularly for women in Africa, and in many parts of SSA, charcoal and fuelwood dominate the available heating energy mix (FIG. 1).

Emphasis on heating fuels has the advantage of opening food microenterprises as a significant market niche for improved energy services. Greater attention to heating energy and switching to more efficient heating fuels, such as liquid liquified petroleum gas, would have a twofold effect. First, doing so would enhance the profitability and employment in the heat-intensive microenterprises and industries. Second, it would substantially reduce aggregate woodfuel consumption in urban areas, thus lowering losses in forest cover in ecologically fragile savannah lands where charcoal is commonly produced in Africa.

Gini–Lorenz Method of Assessing Energy Poverty

Energy consumption has long been seen as a critical indicator of socioeconomic opportunity and national economic activity and growth, as well as a key factor in the human effect on the environment. Several measures of energy usage, most of which rank energy consumption on a per-capita or per-productivity basis (e.g., kilowatt-hours per capita, kilowatt-hours per gross domestic product), are widely used for tracking national



Source: Bailis, Ezzati, and Kammen.[12]

FIGURE 1. Biomass use as wood and as charcoal for cooking and heating across the continent.

economic performance as well for measuring development. Beyond these crude measures, however, few analytic tools exist to examine the interactions between economic activity and energy services, to examine the temporal evolution of energy infrastructure, and to examine the economic and social returns on energy investments. The use of disaggregated consumption data to analyze distributions of energy consumption is extremely rare. However, the significance of energy distribution trends, including equity-related trends, cannot be determined without considering disaggregated data.

A recent report[17] (coauthored by D.K.) presented a set of methods that use Lorenz curves. Such curves are commonly used by economists to estimate income inequality but are largely unused in energy analysis; however, they can play a valuable role in the energy field as a new analytical tool that combines energy access and consumption into one metric. This metric allows for intercountry comparisons while simultaneously providing information about intracountry distributions of energy consumption. Perhaps even more novel and more importantly, Lorenz curves can be used in longitudinal studies to identify distributional trends in a country or region. Longitudinal analyses are particularly important as a tool for understanding changes in energy equity because of policy shifts, to explore the complex relationships between patterns of energy consumption and economic trends, and to examine the potential returns on investment in national or regional energy infrastructure programs.

Energy Lorenz Curves and Gini Coefficients

Lorenz curves and Gini coefficients are widely used in economics to estimate income inequality.[17] In this article we use these metrics to estimate distributions of energy consumption. The Lorenz curve is a ranked distribution of the cumulative percentage of the population of recipients on the abscissa versus the cumulative percentage of the resource distributed along the ordinate axis. The greater the distance this curve is from the diagonal line extending from the origin to the point with coordinates $x = 1$ (or 100%), $y = 1$ (or 100%), the greater the inequality in energy consumption. The Gini coefficient is a numeric measure of inequality that reveals the difference between a uniform distribution and the actual distribution of a resource. It is calculated from the Lorenz curve by taking the ratio between (1) the portion of the area enclosed by the diagonal line and the Lorenz curve and (2) the total area under the diagonal line of uniform distribution. Formally, the Gini coefficient for energy consumption is calculated as

$$G_e = 1 - \sum_i (Y_{i+1} + Y_i) \cdot (X_{i+1} - X_i),$$

where X_i = (number of energy users in population group i)/(total population) and Y_i = (quantity of energy used by population group i)/(total energy use), with Y_i ordered from lowest to highest energy consumption. The Gini coefficient ranges from perfect equity among all members of the population ($G_e = 0$) to complete inequity ($G_e = 1$). Because more than one Lorenz distribution of a resource can lead to the same Gini value, it is often instrumental to view both metrics simultaneously.

Lorenz Curves to Assess Energy Equity

Lorenz curves provide a quantitative measure of different amounts of energy consumption, but they do not directly measure the different utility of energy services. For example, the same amount of energy may be consumed differently in the form of varied energy services (e.g., lighting, heating, appliances) or as a result of various efficiencies of the technologies used. Quantities of energy are a reasonable measure of utility when (1) the average overall efficiency among consumers is approximately constant and (2) the marginal benefit from a unit of energy (e.g., a kilowatt-hour) from consumer to consumer is roughly consistent.

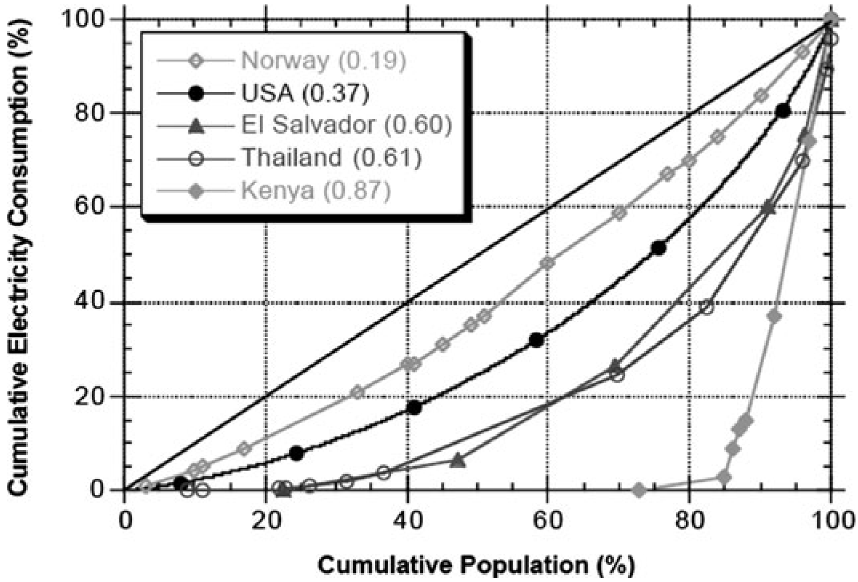
Cross-country Comparisons Highlight Differences in Electricity Equity

To illustrate the application of the Lorenz and Gini metrics, we[17] performed a distributional analysis of residential electricity use for a mix of industrialized and industrializing nations (Fig. 1 in Jacobson *et al.*[17]). In each case we generated Lorenz curves as well as the associated Gini coefficients by using residential electricity consumption survey data that divided the households into groups according to their consumption levels. These countries—Norway, the United States, El Salvador, Thailand, and Kenya—were selected based on a combination of geographic diversity, a desire to include countries with various degrees of economic development, and data availability.

The degree of disaggregation of the population into consumption groups varied from country to country, but in general we could generate reasonable curves with as few as six groups. Data for Norway were national-level data for 1995 aggregated into 20 subgroups according to income and dwelling size. Data for the United States were survey data from 1997 for a nationally representative weighted sample of 5900 homes. Data for El Salvador were national-level data for 2001 aggregated into six groups representing ranges of monthly electricity consumption. Data for Thailand were national-level data for January 2000 aggregated into 11 groups also according to ranges of monthly electricity consumption. Data for Kenya were survey data from 2000 for a nationally representative sample of 2300 homes. For El Salvador, Thailand, and Kenya we added an additional category for households with no electricity access (i.e., these households had no consumption). We also estimated off-grid electricity consumption in households (i.e., from generators, solar energy systems, and car batteries) for Thailand[18] and Kenya.[19,20] In each case we generated the Lorenz curves by ordering the aggregated groups for each country by increasing per-household electricity consumption. We then plotted electricity consumption as a function of population, where population is defined by the number of households. We chose to define population in number of households because data on household size for the different consumption groups were not available for several of the countries. In those countries where information about household size was available, the inclusion of these data did not result in significant changes in the analysis.

The Lorenz curves in FIGURE 2 reveal dramatic differences in the intracountry distribution of residential power consumption between the nations. This finding can be seen through a comparison of the fraction of the population of each country that accounts for half of the total electricity consumption. Norway, where half of residential electricity is used by the top 38% of the household customers, has the most evenly distributed electricity consumption pattern. It is followed by the United States, where half of the electricity is consumed by about 25% of the households, and then El Salvador (≈15%), Thailand (≈13%), and Kenya (≈6%).

Although a complete analysis of the reasons for the differences between the respective distributions is beyond the scope of this article, it is clear from a preliminary analysis that the distributional characteristics of household electricity consumption for the respective countries represented in FIGURE 2 depend heavily on a



Source: Jacobson, Milman and Kammen.[17]

FIGURE 2. Lorenz curves for residential electricity in five countries. The Gini coefficients for residential electricity consumption presented in the legend of the graph (in parentheses) provide a quantitative measure of the distribution of consumption across the population for the respective countries.

combination of the countries' wealth, income distribution, and historical government infrastructure-building policies. For example, we observe a strong relationship between increasing household income and higher electricity consumption levels for the United States.[16] The range of additional factors that shape the Lorenz curves—climate, energy efficiency measures, and the size and geographic distribution of a country's rural population—can provide important constraints on the shape of the curves and is an area of current investigation. This highlights the importance of using energy Lorenz curves and Gini coefficients in combination with broader analyses—including both quantitative and qualitative analytical techniques—of the associated processes and factors that influence the distribution of energy consumption in different countries.

Acknowledgments

We thank the Class of 1935 of the University of California, Berkeley, and the Karsten Family Endowment of the Renewable and Appropriate Energy Laboratory.

Conflicts of Interest

The authors declare no conflicts of interest.

References

1. World Bank. 2001. World Development Report 2000/2001. World Bank. Washington, DC.
2. Karekezi, S. 2002. Poverty and energy in Africa—a brief review. Energy Policy **30:** 915–919.
3. Ezzati, M. & D. Kammen. 2001. Indoor air pollution from biomass combustion and acute respiratory infections in Kenya: an exposure response study. Lancet **358:** 619–625.
4. Cabraal, A., D.F. Barnes, *et al.* 2005. Productive uses of energy for rural development. Annu. Rev. Environ. Resour. **30:** 117–144.
5. Williams, J.H. & R. Ghanadan. 2006. Electricity reform in developing and transition countries: a reappraisal. Energy **31:** 815–844.
6. Wamukonya, N. 2003. Power sector reform in developing countries: mismatched agendas. Energy Policy **31:** 1273–1289.
7. Marandu, E.E. 2002. The prospects of local private investments in Tanzania's rural electrification. Energy Policy **30:** 977–985.
8. Karekezi, S. & W. Kithyoma. 2002. Renewable energy services for rural Africa: is a PV-led renewable energy strategy the right approach for providing modern energy to rural poor of Sub-Saharan Africa? Energy Policy **30:** 1071–1086.
9. Chaurey, A., M. Ranganathan, *et al.* 2004. Electricity access for geographically disadvantaged rural communities—technology and policy insights. Energy Policy **32:** 1693–1705.

10. World Bank. 2000. Reducing the Cost of Grid Extension. World Bank. Washington, DC.
11. Tomkins, R. Extending rural electrification: a survey of innovative schemes. Output-Based Aid (OBA) Book, World Bank: http://rru.worldbank.org/Documents/Other/10ch5.pdf, Accessed: 3/17/2007.
12. Bailis, R., M. Ezzati & D.M. Kammen. 2005. Mortality and greenhouse gas impacts of biomass and petroleum energy futures in Africa. Science **308:** 98–103.
13. Mutimba, S. & M. Barasa. 2005. National charcoal survey: exploring the potential for a sustainable charcoal industry in Kenya. Energy for Sustainable Development Africa. Nairobi.
14. Mills, E. 2000. Global lighting energy use and greenhouse gas emissions. Report, International Association for Energy-Efficient Lighting and Lawrence Berkeley National Laboratory. Berkeley, CA.
15. Jacobson, A. & D.M. Kammen. 2007. Engineering, institutions, and the public interest: evaluating product quality in the Kenyan Solar Photovoltaics Industry. Energy Policy **35:** 2960–2968.
16. Mills, E. 2005. The specter of fuel-based lighting. Science **308:** 1263–1264.
17. Jacobson, A., A.D. Milman & D.M. Kammen. 2005. Letting the (Energy) Gini out of the Bottle: Lorentz curves of cumulative electricity consumption and Gini coefficients as metrics of energy distribution and equity. Energy Policy **33:** 1825–1832.
18. Gastwirth, J.L. & M. Glauberman. 1976. The interpolation of the Lorenz curve and the Gini index from grouped data. Econometrica **44:** 479–483.
19. Greacen, C.S. Personal communication.
20. Field research data from Professor Arnie Jacobson, Humboldt State University.
21. AFREPREN. 2004. The Potential Contribution of Renewables to Africa's Energy Sector: Summary for Policy Makers. African Energy Policy Research Network (AFREPREN). Nairobi.
22. Ministry of Energy, Strategic Plan (Nairobi, Kenya, 2002) http://www.energy.go.ke/publicationsnew.php.
23. USAID. 2005. Zambia: Regulating Rural Electrification Experiences and Lessons Learned *Report Prepared for the United States Agency for International Development*. CORE International, Inc.
24. AFREPREN 2004. African Energy Data and Terminology Handbook: Year 2003–2004 Edition. AFREPREN. Nairobi.