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## Energy Resources and Global Development

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In order to address the economic and environmental consequences of our global energy system, we consider the availability and consumption of energy resources. Problems arise from our dependence on combustible fuels, the environmental risks associated with their extraction, and the environmental damage caused by their emissions. Yet no primary energy source, be it renewable or nonrenewable, is free of environmental or economic limitations. As developed and developing economies continue to grow, conversion to and adoption of environmentally benign energy technology will depend on political and economic realities.

Energy is the lifeblood of technological and economic development. The energy choices made by the United States and the rest of the world have ramifications for economic growth; the local, national, and global environment; and even the shape of international political alliances and national defense commitments. Countries of varying levels of wealth also face different energy challenges (*1*). Here, we discuss the availability of global energy resources, how they are used and by whom, and the consequences of the global distribution and use of energy resources.

Although estimates vary, the world's proved, economically recoverable fossil fuel reserves include almost 1 trillion metric tons of coal, more than 1 trillion barrels of petroleum, and over 150 trillion cubic meters of natural gas (Table 1) (*2*). In addition to fossil fuels, mineral resources important to energy generation include over 3 million metric tons of uranium reserves (*3*). To put this into context, consider that the world's annual 2000 consumption of coal was about 5 billion metric tons or 0.5% of reserves. Natural gas consumption was 1.6% of reserves, whereas oil was almost 3% of reserves, and nuclear electricity generation consumed the equivalent of 2% of uranium reserves (*4*). Reported recoverable reserves have tended to increase

over time, keeping pace with consumption, and now are at or near all-time highs. In relation to current consumption, there remain vast reserves that are adequate for continued worldwide economic development, not even accounting for reserves that will become economically recoverable through continuing discovery and technological advance (*5*). Thus, it seems that the world is not running out of mineral fuels.

Large fossil fuel reserves are concentrated in a small number of countries, with half of the low-income countries and more than a third of the middle-income countries having no fossil fuel reserves whatsoever (*6*). If energy reserves were necessary for economic development, several of the world's poorest nations would be disadvantaged. However, many energy-bereft countries (such as Japan) have become highly developed through sufficient access to international energy markets. Conversely, Nigeria possesses substantial reserves but remains one of the poorest countries, its energy production activities mired in corruption. Thus, simply possessing large fossil energy reserves is of questionable value to a country's development if there is no well-functioning and adequately equitable socioeconomic system enabling it to extract and deploy those energy resources for their full social benefit.

Total global energy use exceeds 370 exajoules (EJ) [350 quadrillion British thermal units (Btus)] per year, which is equivalent to

over 170 million barrels of oil each day (*7*). Approximately 95% of this energy comes from fossil fuels. Global energy consumption draws from six primary sources: 44% petroleum, 26% natural gas, 25% coal, 2.5% hydroelectric power, 2.4% nuclear power, and 0.2% nonhydro renewable energy (*8, 9*). A considerable amount of primary energy is converted to electricity either in the course of initial harvesting (as for hydroelectric, wind, and geothermal) or by combustion (as for fossil, biomass, and waste fuels). These estimates do not include nonmarket fuelwood and farm residues that are prevalent in many developing countries, because global estimates of noncommercial energy use are often incomplete and unreliable. However, the International Energy Agency (IEA) suggests that biomass provides on average one-third of the energy needs in Africa, Asia, and Latin America, and as much as 80 to 90% in the poorest countries of these regions (*10*).

Processing and conversion of primary sources permit enormous versatility in energy use. The end applications of this consumption can be categorized into five major sectors: industry, transportation, agriculture, commercial and public services, and residential (*11*). Developing countries use the most energy in the residential sector (*12*), followed by industrial uses and then transportation (Fig. 1A). The opposite is true for developed countries, where transportation consumes the largest amount of energy, followed by industrial and then residential consumption (Fig. 1B).

Unsurprisingly, the developing and industrialized worlds demonstrate striking disparities in annual energy consumption per capita (*13*). Industrialized country energy use exceeds that of the developing countries for all five end-use sectors by 3 to 14 times, depending on the sector (Fig. 1, A and B) (*14*). In aggregate, the average person in the developing countries consumes the equivalent of 6

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**Table 1. Proved reserves of mineral energy resources, their approximate energy content, and their distribution among income groups in 2001. Petroleum, coal, and natural gas estimates are calculated from data in (29, 32). Uranium estimates are calculated from data in (30).**

Income group	Petroleum			Coal			Natural gas			Uranium†		
	10 <sup>9</sup> barrels	EJ*	% total	10 <sup>6</sup> metric tons	EJ	% total	10 <sup>12</sup> cubic m	EJ	% total	1000 metric tons	EJ	% total
Poorest 10%	24	140	2.33	475.4	10	0.05	3.7	140	2.41	193.5	15,000	5.91
Low-income	49.5	290	4.80	133090.5	2700	13.54	12.9	490	8.37	488.8	38000	14.92
Middle-income	723.6	4300	70.14	439213.1	8800	44.69	105.2	4000	68.12	1282.2	99000	39.14
Low- + middle-income (developing)	773.1	4500	74.93	572303.6	11000	58.24	118.2	4500	76.49	1771	140000	54.06
High-income (developed)	258.6	1500	25.07	410409.1	8200	41.76	36.3	1400	23.51	1490.4	110000	45.49
Richest 10%	38.6	230	3.74	317104.1	6300	32.27	9.5	360	6.13	332.1	26000	10.14
Total	1031.7	6100		982712.7	20000		154.5	5900		3276.1	250000	

\*EJ = exajoules = 10<sup>18</sup> joules (9.48 × 10<sup>14</sup> Btus).

†Proved reserves of uranium refer to RARs described by the International Atomic Energy Agency.

barrels of oil [(34 gigajoules (GJ) or 32 million Btus] annually, whereas the average person in the developed world consumes nearly 40 barrels (220 GJ or 210 million Btus) (table S1) (15). Residents of the poorest 10% of countries consume less than one barrel of oil equivalent per year per capita, whereas their counterparts in the richest 10% of countries consume over 60 times as much. Also striking are disparities within the developing world. On an annual per-capita basis, the middle-income countries use four times as much energy as their low-income counterparts.

These relationships between wealth and energy consumption suggest that as a country becomes richer, its people tend to consume substantially more energy (table S1). However, looking at energy use within the high-income group alone, the correlation is weaker. For example, Norway has a gross national income per capita (GNI/pop) of U.S. \$34,530 and Japan is slightly higher at U.S. \$35,620, but energy consumption per capita is lower in Japan: 150 GJ compared to 250 GJ for Norway. This discrepancy is probably due to the availability of relatively inexpensive hydroelectric power in Norway, whereas Japan, possessing fewer local resources, has greater incentives to be more energy efficient. Therefore, although at a coarse scale energy consumption per capita increases with economic growth, there are different paths that a particular country's energy system can take in its development, with some paths resulting in greater efficiency and less consumption than others.

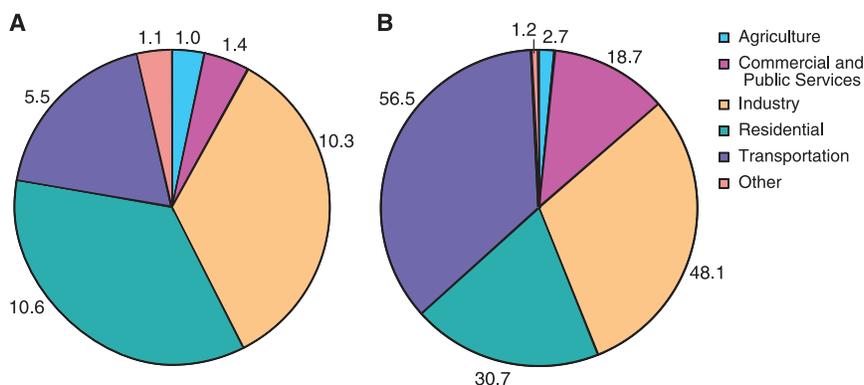
Moreover, when one examines energy use per dollar of gross domestic product (GDP), the low-income countries use more energy to create a dollar of GDP than do the high-income countries, because of greater use of more energy-efficient technologies as a country develops (table S1) (16). Furthermore, as cleaner energy-efficient technologies gener-

ated by the industrialized countries become cheaper, the growing economies of the developing world become more likely to adopt them, bypassing more wasteful and polluting technologies. For example, countries such as China, India, Brazil, and the Philippines have been installing high-voltage direct-current cables to deliver electricity with greater reliability and efficiency than the alternating-current cables prevalent in the United States.

The data also strongly indicate that the world is heavily dependent on fossil fuel energy, with only about 5% coming from other sources, and it will remain so barring substantial technological change. In the near term, this continued dependence is partially due to the paucity of convenient alternatives to petroleum products as fuels in the transportation sector, which consumes the most energy in the developed world. Currently, transportation in the poorest decile of countries consumes less than 3% of the energy consumed by that sector in the richest countries. As developing countries become richer and expand their transportation networks, petroleum products will likely fuel them. The

industrial sector of the developed world also relies heavily on fossil fuels. Institutional inertia, as well as the cost of replacing capital-intensive, fossil energy-dependent infrastructure, slow the pace at which nonfossil substitutions can occur.

Between 1980 and 2001, worldwide consumption of petroleum, coal, and natural gas increased by 22, 27, and 71%, respectively. Concurrently, annual world carbon dioxide (CO<sub>2</sub>) emissions from the consumption and flaring of fossil fuels, implicated as the predominant cause of global climate change, increased from 5 billion to 6.6 billion metric tons carbon equivalent, with relatively steady increases occurring for all income groups (fig. S1). Fossil fuel consumption also results in lesser emissions of other greenhouse gases (GHGs), such as carbon monoxide, methane, and volatile organic compounds (VOCs), not to mention nitrous oxides (NO<sub>x</sub>) that facilitate the formation of heat-trapping tropospheric ozone. Although fossil fuel reserves are in no danger of diminishing in the foreseeable future, should the world continue to consume all or even a large fraction of those



**Fig. 1.** Per-capita energy consumption by sectoral end use in (A) the developing world and (B) the developed world (in gigajoules)

resources though normal combustion processes, the release of additional GHGs into the atmosphere would likely have substantial consequences for the global climate. According to the Intergovernmental Panel on Climate Change (IPCC), climate models generally predict that continued emissions of anthropogenic GHGs beyond the sequestration capacity of natural sinks will result in not only increased mean temperatures but also more frequent extreme climate events such as droughts and intense storms, with significant consequences for ecosystems, agricultural productivity, and human welfare (17).

Besides GHG emissions, fossil fuel production and use come with other environmental costs. Fossil fuel exploration requires seismic testing and road building that can harm wildlife and fragment habitats. Extraction requires the replacement of natural habitat with infrastructure and can lead to leaking of fuels and toxic byproducts, such as arsenic, cadmium, and mercury, into the local environment. In the case of oil, spills that occur during transportation and refining also damage local environments. Sulfur dioxide, NO<sub>x</sub>, and VOCs released from coal and petroleum combustion cause a myriad of environmental problems, including acid rain, smog, and nitrogen loading.

Furthermore, the traditional alternatives to fossil energy—hydroelectricity and nuclear power—have environmental and social costs that limit their viability as long-term fossil fuel substitutes. In addition to the drawback of being near saturation, hydroelectric power infrastructure causes dramatic alterations in riparian ecosystems and often the inundation of human settlements and terrestrial habitat. Fissile nuclear power, too, is unlikely to expand because of objections to waste disposal and concerns over weapons proliferation.

It should be noted that no primary energy source and its associated technology are completely free of environmental and other drawbacks. Wind-powered electric turbines require the installation of infrastructure, can cause the death of migratory birds, and elicit local objections on aesthetic grounds. Geothermal plants emit CO<sub>2</sub> and hydrogen sulfide. Wind, solar, and geothermal systems are capital-intensive and their viability is geographically limited (18). Without affordable and practical electricity storage, intermittency is also a problem for wind and solar power. The domestically combusted biomass used in developing countries is often a health hazard because of indoor smoke inhalation (19), and mass-produced fuels derived from biomass place greater burdens on agricultural and forest productivity. Even the highly tout-

ed hydrogen fuel cell, which releases only water vapor, would initially require fossil fuels as hydrogen fuel stock (20). In order to minimize environmental damage relative to the benefits of energy consumption, a sustainable, environmentally benign energy system, or at least the transition to one, will involve a heterogeneous portfolio of renewable primary sources in order to minimize the environmental impact of any particular source.

The environmental costs of fossil, hydroelectric, and nuclear energy consumption could drive the world toward alternative sources before scarcity becomes a significant issue. Government programs to reduce the negative environmental impacts of fossil fuel production and consumption have the same effect as scarcity-induced price increases, and would stimulate (or mandate) new energy technologies that in-

**Table 2. Current average European costs of conventional and renewable energy production (1/100th of a Euro in base year 1990 values per kilowatt-hour). PVs, photovoltaics; 1 Euro = ~ U.S. \$1.17. [Source: Commission of the European Communities, *Green Paper Towards a European Strategy for the Security of Energy Supply* (Commission of the European Communities, Brussels, 2000).]**

Conventional energy			Renewable alternatives		
Coal	GTCC	Nuclear	Wind	Solar PVs	Bio-energy
3.4	3.1	4.0	7.1	65.5	4.8

crease efficiency, mitigate pollution, and substitute for fossil energy. Policy mechanisms to achieve these ends include environmental standards, fuel and emission taxes, subsidies for renewable energy production, mandated diversified energy portfolios, and emission permit-trading schemes. In the United States and elsewhere, several of these policies (such as regulated limits, emission fees, and tradable permits) have been successfully implemented to reduce noncarbon air pollution, improve air quality, and reduce acid rain (21–24).

Given growing environmental concerns, the future use of fossil resources will likely not follow the standard combustion path of the past but will involve processes with increased efficiency, lower localized air pollution, and perhaps carbon capture and sequestration before, after, or instead of combustion (25). Electricity in particular

will remain the most important end-use energy form because of its flexibility in both generation and use. Renewable sources of electricity from solar, wind, geothermal, and tidal power are currently available, but they remain the least consumed form of energy across all income groups (26). Per-capita consumption rates do not exceed 1 MJ (100,000 Btus) per year in the developing-country categories (less than a gallon of oil equivalent), and do not exceed 1 GJ (1 million Btus) per year in the high-income category, with only 24 industrialized countries consuming significant amounts (27).

Renewable energy sources will become prevalent only if they can be more competitive than fossil fuels in terms of relative prices (Table 2). Competition from lower-cost conventional power production, notably by gas turbine combined cycle (GTCC) systems, will continue to undercut renewables, even with falling costs (28). Rather than wait for scarcity-induced price rises, governments can accelerate the adoption of renewables with two coordinated and self-reinforcing actions. First, governments can adopt a variety of R&D policies (usually in the form of subsidies) that would bring down the price and improve the performance of renewables in comparison with fossil fuels. Second, they can raise the price of fossil fuels through carbon taxes or permits and thereby tilt the economics toward renewables. These actions serve to push renewables forward by subsidizing their development, while at the same time pulling renewables into the market by disadvantaging the price competitiveness of fossil fuels.

As the recent blackouts in North America and Italy made clear, even energy systems in the richest countries are far from problem-free. Similar systems in the developing world may be even more trouble-fraught as they develop. However, sub-Saharan Africa and other poor countries will probably never have an electricity grid exactly like those of today's high-income countries, even when they have pulled themselves out of wrenching poverty.

In the same way that the developing world is bypassing the paired-copper-wire grid that characterizes telephony in the developed world and is leaping directly to cellular communication, so too is it likely to rely much less heavily on our technological model of electricity generation. Rather than adopting a system with large central-station power plants generating electricity and distributing it over long distances, we speculate that the developing countries, especially the poorest, are more likely to

eventually adopt smaller and less capital-intensive microturbines and renewable sources of electricity generation such as biomass, wind, and solar that are closer to the point of use. These applications will bring with them their own sets of problems, but will enable the developing world to avoid others.

Will the world make a transition to alternative, more renewable sources of energy? The simple answer is yes, if only because, in time, supplies of fossil fuels will become too costly. For the next 25 to 50 years, however, this seems not to be a likely prospect. With energy choices driven by relative prices, fossil fuels will dominate energy use for many years to come. These fuels remain relatively inexpensive, and they are supported by a very broad and long-lived infrastructure of mines, wells, pipelines, refineries, gas stations, power plants, rail lines, tankers, and vehicles. Very powerful political constituencies exist worldwide to ensure that investments in this infrastructure are protected.

If fossil fuel depletion occurs more rapidly than we expect, or if governments enact policies that artificially increase fossil fuel prices, renewables and alternative energy sources may come online more quickly. The requisite political will and financial support to enact such changes will occur only when societies and their governments decide that the benefits of fossil fuel consumption do not make up for the negative effects on environmental health and human welfare of fossil fuel dependence.

#### References and Notes

- We analyzed year 2000 data from 211 countries, using the World Bank's method of distinguishing between low-, middle-, and high-income countries according to GNI/pop. We refer to low- and middle-income countries jointly as developing countries, and high-income countries are considered industrialized or developed countries. Of the countries considered in this analysis, approximately 75% fall into the former category. Countries are low-income if GNI/pop is less than U.S. \$750 (69 countries, including the Congo, India, and Indonesia); middle-income if GNI/pop is between U.S. \$750 and \$9250 (85 countries, including Argentina, Mexico, and Turkey); or high-income if GNI/pop is greater than U.S. \$9250 (57 countries, including the United States, Japan, and Western Europe). We have also identified those countries comprising the poorest 10% (such as Cambodia, Chad, and Tajikistan) and the richest 10% (such as the United States, Singapore, and the United Kingdom). The developing-country group is heterogeneous in resource endowments and development conditions, whereas classification as a developed country does not imply a preferred or final stage of development. GNI/pop is a convenient criterion among many metrics for levels of development and does not necessarily reflect development status. GNI, GDP, and population data for 2000 are drawn from the *World Development Indicators 2002*, published by the World Bank. Population, GNI/pop, and income categorization for all 211 countries are available at (37).
- These numbers are based on year 2001 data from (29). Reserves include only resources that are identified as economically and technically recoverable with current technologies and prices. Other resources with foreseeable or unknown potential for recovery exist but are not included in this report, because estimates are often highly speculative and unreliable, particularly estimates of resources in developing countries. Reserve estimates tend to expand overall with time, as technology increases the number of economically recoverable reserves.
- These numbers are based on year 2001 data from (30). This estimate includes reasonably assured resources (RARs) identified by the IAEA and does not include other potential resources and secondary supplies from reprocessed uranium, re-enriched uranium, and highly enriched uranium from the dismantlement of nuclear weapons. A list of reserves by country is available at (37).
- However, 42% of uranium used for nuclear electricity generation is currently supplied by secondary sources, so the actual consumption of uranium reserves is less than this estimate suggests.
- It should be noted that the three major fossil fuels are not perfect substitutes for each other, particularly in the short term. Petroleum derivatives offer versatility in use and ease of transport that make them ideal for the transportation sector. Coal is the most abundant fossil fuel but generates the most airborne pollutants. Hence, coal-fired electricity generation plants are gradually giving way to gas-fired plants. Natural gas is the cleanest-burning and most energy-efficient fossil fuel, but supply is currently hindered by insufficient extraction and transport infrastructure, such as regasification and storage facilities for importing liquefied natural gas from overseas.
- Similarly, the majority of reserves in the developed countries also are concentrated in a relatively few nations, notably the United States and several of the wealthier oil-producing Middle Eastern states. A map and list of global reserves by country as well as a more detailed descriptive analysis are available at (37).
- These numbers are based on year 2000 data from (29).
- Renewables include energy generated from sources such as geothermal, wind, solar, wood, and waste fuels. This percentage does not include the domestic use of fuelwood and other biomass common in developing countries, but does include energy derived from electric power generation using these fuels.
- Global maps and tables of consumption by energy source are available at (37).
- S. L. D'Apote, in *Biomass Energy: Data, Analysis and Trends* (International Energy Agency, Vienna, 1998), pp. 1–31.
- The year 2000 data used to examine sectoral uses of energy are drawn from *Energy Balances of the OECD Countries and Energy Balances of the Non-OECD Countries*, compiled by the International Energy Agency. These data exist only for 133 countries and are not directly comparable to the data discussed above for 200-plus countries provided by the Energy Information Administration (EIA) of the U.S. Department of Energy. This data set includes the consumption of combustible renewables and waste, such as fuelwood, whereas the EIA data set does not. Inferences drawn from direct comparison of the two different sets of data and analyses would not be robust. More detailed descriptions of end-use sectors as defined by the International Energy Agency are available at (37).
- Residential energy consumption in many regions that are included among the developing states consists predominantly of combustible materials and waste such as fuelwood, manure, and other biofuels, rather than the forms of energy described in the analyses above. Biomass is often the only available and affordable source of energy for basic needs, such as cooking and heating, for large portions of rural populations and for the poorest sections of urban populations in developing countries.
- Maps and tables of per-capita aggregate energy consumption by country are available at (37).
- Country tables of per-capita energy consumption by end use are available at (37).
- These numbers are based on year 2000 data from (29). Per-capita consumption is calculated by dividing aggregate energy consumption by population and does not account for imports and exports of energy embodied in the trade of goods.
- It is generally accepted practice to use GDP rather than GNI when discussing the energy intensity of economic output. Our conclusions would be no different if we used GNI. Global maps and tables of aggregate energy consumption per dollar of GDP are available at (37).
- IPCC, *Climate Change 2001: The Scientific Basis* (IPCC, Cambridge, 2001).
- Coastal areas and plains are ideal for wind power, sunny areas such as equatorial regions for solar power, and volcanic basins for geothermal energy.
- These fuels are also often used inefficiently because of poor technology (such as a lack of closed stoves or ventilation) and have negative health effects, depending on their method of use. Thus, the health hazards associated with traditional biomass are partly the consequence of sociocultural and developmental problems and can be mitigated with simple technological improvements.
- In the case of hydrogen fuel cells, one must also consider the environmental consequences of increased levels of water vapor in the atmosphere, should this technology be widespread in the future.
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- S. Anderson, R. Newell, *Resources for the Future Discussion Paper 02-68* (Resources for the Future, Washington, DC, 2003).
- Renewables referred to in this discussion include electricity generated from geothermal, solar, wind, biomass, and waste sources, but not domestically combusted fuels.
- These numbers are based on year 2000 data from (29).
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- International Energy Annual 2001 Edition* (EIA, U.S. Department of Energy, Washington, DC, 2003).
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- See [www.rff.org/energyresources/](http://www.rff.org/energyresources/).
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#### Supporting Online Material

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SOM Text

Fig. S1

Table S1

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