CORRECTED 7 SEPTEMBER 2007; SEE LAST PAGE

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PERSPECTIVE

Ethanol for a Sustainable Energy Future

José Goldemberg*

Renewable energy is one of the most efficient ways to achieve sustainable development. Increasing its share in the world matrix will help prolong the existence of fossil fuel reserves, address the threats posed by climate change, and enable better security of the energy supply on a global scale. Most of the "new renewable energy sources" are still undergoing large-scale commercial development, but some technologies are already well established. These include Brazilian sugarcane ethanol, which, after 30 years of production, is a global energy commodity that is fully competitive with motor gasoline and appropriate for replication in many countries.

A sustainable energy future depends on an increased share of renewable energy, especially in developing countries. One of the best ways to achieve such a goal is by replicating the large Brazilian program of sugarcane ethanol, started in the 1970s.

The World Commission on Environment and Development (WCED) in 1987 defined "sustainable development" as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (*1*). The elusiveness of such a definition has led to unending discussions among social scientists regarding the meaning of "future generations."

However, in the case of energy, exhaustible fossil fuels represent ~80% of the total world energy supply. At constant production and consumption, the presently known reserves of oil will last around 41 years, natural gas 64 years, and coal 155 years (*2*). Although very simplified, such an analysis illustrates why fossil fuels cannot be considered as the world's main source of energy for more than one or two generations. Besides the issue of depletion, fossil fuel use presents serious environmental problems, particularly global warming. Also, their production costs will increase as reserves approach exhaustion and as more expensive technologies are used to explore and extract less attractive resources. Finally, there are increasing concerns for the security of the oil supply, originating mainly from politically unstable regions of the world.

Except for nuclear energy, the most likely alternatives to fossil fuels are renewable sources such as hydroelectric, biomass, wind, solar, geothermal, and marine tidal. Figure 1 shows the present world energy use.

Fossil fuels (oil, coal, and gas) represent 80.1% of the total world energy supply, nuclear energy 6.3%, and renewables 13.6%. The largest part is traditional biomass (8.5% of total primary energy), which is used mainly in inefficient ways, such as in highly pollutant primitive cooking stoves used by poor rural populations, leading in many cases to deforestation.

The "new renewable energy sources" amount to 16 exajoules (1 EJ = 10^{18} J), or 3.4% of the total. Table 1 shows a breakdown of the contribution of new renewables, which include small hydropower plants. Many of these technologies are still undergoing large-scale commercial development, including solar, wind, geothermal, and modern biomass. The largest part (1.9% of the total) is modern biomass, which refers to biomass produced in a sustainable way and used for electricity generation, heat production, and transportation of liquid fuels. It includes wood and forest residues from reforestation and/or sustainable management, as well as rural (animal and agricultural) and urban residues (including solid waste and liquid effluents).

From the perspective of sustainable energy development, renewables are widely available, ensuring greater security of the energy supply and reducing dependence on oil imports from politically unstable regions. Renewables are less polluting, both in terms of local emissions (such as particulates, sulfur, and lead) and greenhouse gases (carbon dioxide and methane) that cause global warming. They are also more labor-intensive, requiring more workforce per unit of energy than conventional fossil fuels (*3*).

Although technologically mature, some of the renewable sources of energy are more expensive than energy produced from fossil fuels. This is particularly the case for the "new renewables." Traditional biomass is frequently not the object of commercial transactions and it is difficult to evaluate its costs, except the environmental ones. Cost continues to be the fundamental barrier to widespread adoption of traditional biomass despite its attractiveness from a sustainability perspective.

A number of strategies have been adopted by governments in the industrialized countries and international financial institutions to encourage the use of "new renewables," and there have been several successes, based on the use of tax breaks, subsidies, and renewable portfolio standards (RPS). Examples are the large growth (of more than 35% per year, "albeit" from a low base value) for wind and solar photovoltatics in industrialized countries such as Denmark, Germany, Spain, and the United States (*4*). These technologies are slowly spreading to developing countries through several strategies.

In developing countries, the best example of a large growth in the use of renewables is given by the sugarcane ethanol program in Brazil. Today, ethanol production from sugarcane in the country is 16 billion liters (4.2 billion gallons) per year, requiring around 3 million hectares of land. The competition for land use between food and fuel has not been substantial: Sugarcane covers 10% of total cultivated land and 1% of total land available for agriculture in the country. Total sugarcane crop area (for sugar and ethanol) is 5.6 million hectares.

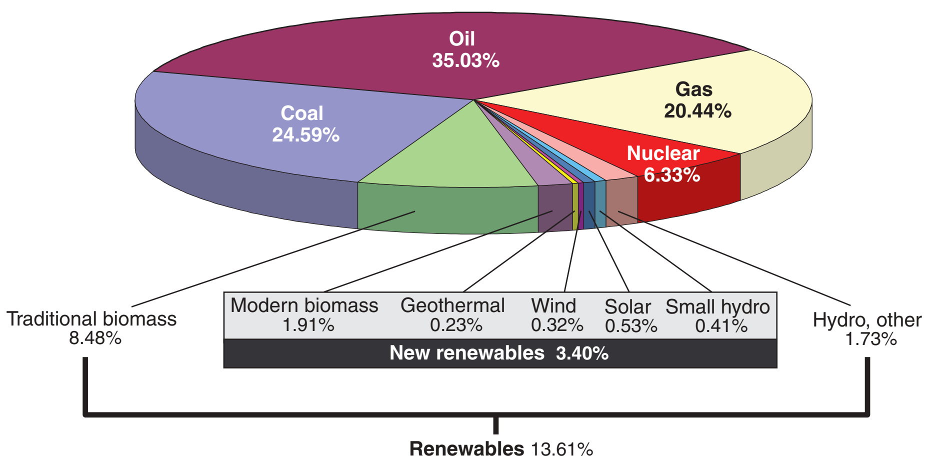

Fig. 1. World total primary energy supply 2004, shares of 11.2 billion tons of oil equivalent, or 470 EJ (*15*, *16*).

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Production of ethanol from sugarcane can be replicated in other countries without serious damage to natural ecosystems. Worldwide, some 20 million hectares are used for growing sugarcane, mostly for sugar production (*5*). A simple calculation shows that expanding the Brazilian ethanol program by a factor of 10 (i.e., an additional 30 million hectares of sugarcane in Brazil and in other countries) would supply enough ethanol to replace 10% of the gasoline used in the world. This land area is a small fraction of the more than 1 billion hectares of primary crops already harvested on the planet.

What was the process that established firmly the ethanol program in Brazil? In the late 1970s, the Brazilian Federal Government mandated the mixture of anhydrous ethanol in gasoline (blends up to 25%) and encouraged car makers to produce engines running on pure hydrated ethanol (100%). Brazilian adoption of mandatory regulations determining the amount of ethanol to be mixed with gasoline (basically a Renewable Portfolio Standard for fuel) was essential to the success of the program. The motivation was to reduce oil imports that were consuming one-half of the total amount of hard currency from exports. Although it was a decision made by the federal government during a military regime, it was well accepted by the civil society, agricultural sector, and car manufacturers. Similar policies are being considered by the European Union, Japan, and several states in the United States.

Such a policy decision created a market for ethanol, and production increased rapidly. Ethanol costs declined along a "learning curve" (*6*) as production increased an average 6% per year, from 0.9 billion gallons in 1980 to 3.0 billion gallons in 1990 and to 4.2 billion gallons in 2006. The cost of ethanol in 1980 was approximately three times the cost of gasoline, but governmental cross-subsidies paid for the price difference at the pump. The subsidies came mostly from taxes on gasoline and were thus paid by automobile drivers. All fuel prices were controlled by the government. Overall subsidies to ethanol are estimated to be around US$30 billion over 20 years (*7*), but were more than offset by a US$50 billion reduction of petroleum imports as of the end of 2006. Since the 1990s subsidies have been progressively removed, and by 2004 ethanol became fully competitive with gasoline on the international markets without government intervention. Subsidies for ethanol production are a thing of the past in Brazil (Fig. 2), because new ethanol plants benefit from the economies of scale and the modern technology available today, such as the use of high-pressure boilers that allow cogeneration of electricity, with surpluses sold to the electric power grid.

The Brazilian ethanol program started as a way to reduce the reliance on oil imports, but it was soon realized that it had important environmental and social benefits (*8*). Conversion to ethanol allowed the phasing-out of lead additives and MTBE (methyl tertiary butyl ether) and reduced sulfur, particulate matter, and carbon monoxide emissions. It helped mitigate greenhouse gas emissions efficiently, by having a net positive energy balance (renewable energy output versus fossil fuel inputs); also, sugarcane ethanol in Brazil costs less than other present technologies for ethanol production (Table 2) and is competitive with gasoline in the United States, even considering the import duty of US$0.54 per gallon and energy-efficiency penal-

Table 1. "New renewables," by source in 2004 (*15*); updated with data from (*4*, *16*). Assumed average conversion efficiency: for biomass heat, 85%; biomass electricity, 22%; biomass combined heat and power (CHP), 80%; geothermal electricity, 10%; all others, 100%.

Source/ technology	2004	
	Exajoules (EJ)	Share in this sector
Modern biomass energy		
Total	9.01	56.19%
Bioethanol	0.67	
Biodiesel	0.07	
Electricity	1.33	
Heat	6.94	
Geothermal energy		
Total	1.09	6.77%
Electricity	0.28	
Heat	0.30	
Small hydropower		
Total	1.92	12.00%
Wind electricity		
Total	1.50	9.35%
Solar		
Total	2.50	15.63%
Hot water	2.37	
Photovoltaic electricity, grid	0.06	
Photovoltaic electricity, off-grid	0.06	
Thermal electricity	0.01	
Marine energy (tidal)		
Total	0.01	
Total	16.03	100.00%

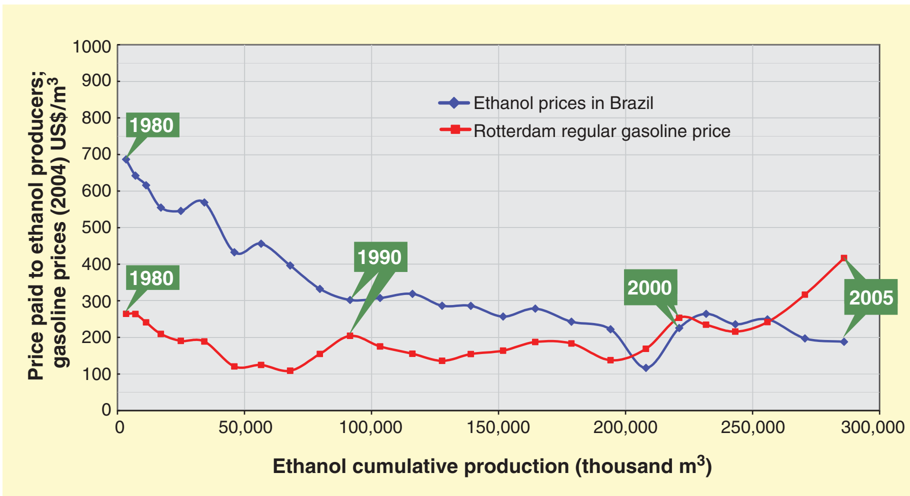

Fig. 2. Ethanol learning curve in volume, comparing the price paid to ethanol producers in Brazil with the price of gasoline in the international market of Rotterdam (*6*).

Table 2. Ethanol costs and energy balances.

Feedstock	Cost (US$ per gallon)	Energy balance (renewable output to fossil input)
Sugarcane, Brazil		10.2 (*18*)
2006, without import tax	0.81 (*17*)	
2006, with U.S. import tax	1.35 (*9*, *17*)	
Sugar beet, Europe, 2003	2.89 (*17*)	2.1 (*19*)
Corn, U.S., 2006	1.03 (*17*)	1.4 (*9*, *11*)
Cellulose ethanol, U.S.		10.0 (*11*)
Achieved in 2006	2.25 (*11*)	
Target for 2012	1.07 (*11*)	

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ties (30% or less with modern flexible fuel vehicle technologies) (*9*). The summer wholesale price of gasoline in the United States is about \$1.9 per gallon; the corn ethanol wholesale price is around US\$2.5 per gallon (*10*). Cellulose ethanol is a promising option in the long term, but is not being produced on a commercial scale. The longer-term target is as low as 60 cents per gallon, but this will require major advances in producing, collecting, and converting biomass. A more realistic research target is to reduce the cost of production to US\$1.07 per gallon until 2012 (*11*).

The development of other biomass-derived fuels in Brazil or elsewhere could benefit from such insights. Promising candidates along those lines are the following:

1) The production of ethanol from cellulosic materials, which still requires considerable R&D effort before reaching the production stage. If the technology for such conversion is firmly established, it would open enormous opportunities for the use of all kinds of wood and other biomass feedstocks for ethanol production.

2) The enhanced use of biogas produced from microbial conversion in landfills of municipal solid wastes, wastewater, industrial effluents, and manure wastes will abate a considerable share of greenhouse gases that would be released to the atmosphere, replacing also fossil fuels for heat and electricity production.

3) The use of planted forests for the production of electricity either by direct combustion or by gasification and use of highly efficient gas turbines will also replace efficiently coal, natural gas, oil, and even nuclear sources. Reforested wood can also reduce the need for deforested fuel wood, controlling efficiently releases of greenhouse gases through market-friendly initiatives.

The ethanol program in Brazil was based on indigenous technology (both in the industrial and agricultural areas) and, in contrast to wind and solar photovoltaics, does not depend on imports, and the technology can be transferred to other developing countries.

Until breakthrough technologies become commercially viable, an alternative already exists: Many developing countries have suitable conditions to expand and replicate the Brazilian sugarcane program, supplying the world's gasoline motor vehicles with a renewable, efficient fuel.

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20. I thank O. Lucon and J. R. Moreira for useful discussions and contributions.

10.1126/science.1137013

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PERSPECTIVE

Renewable Energy Sources and the Realities of Setting an Energy Agenda

Janez Potočnik

The European Commission has been devoting considerable attention to energy issues. This Perspective describes recent progress in Europe toward achieving goals for renewable energy use, and the role that technology can play, as well as the new Strategic Energy Package.

Energy is undoubtedly moving up the political agenda as an issue that needs to be addressed urgently. If last year's threats to European gas supplies during the dispute between Russia and Ukraine did not show the immediacy of the challenges such as energy supply, then the report toward the end of last year by Sir Nicholas Stern (*1*) on the economics of climate change must surely have rung a warning bell.

The European Commission has been devoting considerable attention to energy issues for some time now. We were leaders in the process that brought about the Kyoto Protocol and have developed the first large-scale emissions trading scheme in the world. In March 2006, we published a Green Paper on energy (*2*), which we have now, at the beginning of 2007, followed up with a strategic energy package (*3*) addressing energy policy in general and also outlining future European policy on various specific elements.

One of these specific elements will be the elaboration at the European level of a Strategic Energy Technology Plan (*4*). Research and technology will undoubtedly be crucial to cracking the energy and climate change nut. A recent study published by the European Commission (Fig. 1) (*5*) shows that, if existing trends

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ERRATUM

Post date 7 September 2007

Special Issue on Sustainability and Energy: Perspectives: "Ethanol for a sustainable energy future" by J. Goldemberg (9 February 2007, p. 808). There are numerical errors in Table 1. Under the heading "Geothermal energy," the value for "Total" should be 1.08, and the value for "Heat" should be 0.80.

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Science

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Science **315** (5813), 808-810.
DOI: 10.1126/science.1137013

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