

RENEWABLE ENERGY SOURCES

Antonia V. Herzog
Timothy E. Lipman
Daniel M. Kammen

Energy and Resources Group
Renewable and Appropriate Energy Laboratory (RAEL)
University of California, Berkeley, USA
Email: aherzog@socrates.berkeley.edu, telipman@socrates.berkeley.edu,
dkammen@socrates.berkeley.edu
URL: <http://socrates.berkeley.edu/~rael>

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Glossary

- Amorphous silicon (a-Si):** A glassy alloy of silicon and hydrogen (about 10 percent) used in thin-film photovoltaic solar cells to convert sunlight to electricity.
- Anaerobic Digestion:** Combustible gas called biogas produced from biomass through low temperature biological processes.
- Anthropogenic:** Man made.
- Bagasse:** The fiber residue that remains after juice extraction from sugarcane.
- Baseload:** That part of total energy demand that does not vary over a given period of time.
- Biodiversity:** In the most general sense, all aspects of variety in the living world: the richness of living forms ranging from genes and molecules to entire ecosystems, forms and structures.
- Bioenergy:** The conversion of biomass into useful forms of energy such as heat, electricity and liquid fuels.
- Benefit-cost ratio (BCR):** A ratio of estimates of the long-term benefits and costs from an economic decision, typically discounted to net present values.
- Biogas:** The common name for a gas produced by the biological process of anaerobic (without air) digestion of organic material.
- Biomass:** Organic, non-fossil material of biological origin constituting an exploitable energy source.
- Capital costs:** Costs associated with the capital or investment expenditures on land, plant, equipment and inventories. Unlike labor and operating costs these are independent of the level of output.
- Carbon Dioxide (CO₂):** The gas formed in the ordinary combustion of carbon, given out in the breathing of animals, burning of fossil fuels, etc. Human sources are very small in relation to the natural cycle.
- Carbon tax:** A tax based on the carbon content of a fuel so as to internalize environmental externalities associated with climate change.
- Clean Energy Technologies (CET):** Electricity and/or heat producing systems that produce negligible or minimal amounts of environmental pollution compared with conventional technologies.
- Climate change:** A change in climate, which is attributed directly, or indirectly to human activity that alters the composition of the global atmosphere and is in addition to natural climate variability observed over comparable time periods.
- Combined heat and power (CHP), or cogeneration systems:** The waste heat from a steam turbine producing electricity is recovered and used for meeting industrial process heat needs.
- Commercial Energy:** Energy supplied on commercial terms. Distinguished from non-commercial energy comprising fuelwood, agricultural wastes and animal dung collected usually by the user.
- Dematerialization:** Energy conservation, less new energy needed for future economic growth.
- Discount rate:** The annual rate at which the value of future costs is reduced so as to be comparable to the value of present costs.
- DOE:** Department of Energy.
- Economies of scale:** Reductions in manufacturing costs that accrue through increases in the scale of production and the resulting efficiencies in production.
- Emission permit:** A non-transferable or tradable allocation of entitlements by a government to an individual firm to emit a certain amount of a substance.

Energy crops: Crops designed either exclusively for a biomass energy feedstock or for the coproduction of energy and other agricultural products.

Environmental costs: real economic costs to society, borne through damages or alterations to an environmental medium.

EPA: Environmental Protection Agency, a US government agency.

Ethanol: Clean burning high efficiency fuel produced from the fermentation of biomass that can substitute for conventional liquid petroleum fuels such as gasoline and kerosene.

Exajoules (EJ): 10^{18} joules, a unit of measurement of energy, which is the capacity for doing work.

Experience curve: A curve that plots the reduction in unit manufacturing cost of a given product, typically as a function of accumulated production. Similar to a progress ratio, but typically at the industry level rather than the individual firm level.

Externalities: By-products of activities that affect the well being of people or damage the environment, where those impacts are not reflected in market prices.

Fischer-Tropsch (F - T) liquids: A class of synthesized hydrocarbons, which is a petroleum-like liquid fuel, produced from gasified biomass.

Fluidized beds: Beds of burning fuel and non-combustible particles kept in suspension by upward flow of combustion air through the bed. Limestone or coal ash are widely used non-combustible materials.

Forward-price: A strategy for pricing whereby the initial price is set below total manufacturing cost in order to capture market share and economies of scale so that the manufacturing cost drops below the price and the initial losses can be recouped.

Fossil fuels: A device that produces electricity directly from chemical reactions in a galvanic cell wherein the reactants are replenished.

Gasification: Combustible gas called producer-gas produced from biomass through a high temperature thermochemical process. Involves burning biomass without sufficient air for full combustion, but with enough air to convert the solid biomass into a gaseous fuel.

Geothermal: Natural heat extracted from the earth's crust using its vertical thermal gradient, most readily available where there is a discontinuity in the earth's crust (e.g. where there is separation or erosion of tectonic plates).

Greenhouse gas (GHG): Gases which, when concentrated in the atmosphere, prevent solar radiation trapped by the Earth and re-emitted from its surface from escaping. The result is a rise in the Earth's near surface temperature. The phenomenon was first described by Fourier in 1827, and first termed the greenhouse effect by Arrhenius in 1896. Carbon dioxide is the largest in volume of the greenhouse gases. The others are halocarbons, methane (CH_4), nitrous oxide (N_2O), ozone (O_3), hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride.

Integrated gasification combined cycle (IGCC): An IGCC system involves sizing and drying of the feedstock, followed by thermochemical gasification to produce a combustible gas, cooling and cleaning of the gas, and combustion in a gas turbine. Steam is raised using the hot exhaust of the gas turbine to drive a steam turbine that generates additional power and/or delivers lower pressure steam for heating purposes. The cascading of a gas turbine and a steam turbine in this manner is commonly called a combined cycle.

Intermittent renewable: A renewable energy system that operates periodically rather than constantly, such as when the sun is shining or wind is blowing.

Kilowatthour (kWh): A unit of measure of energy ($1\text{kWh} = 3.6 \times 10^6 \text{J}$).

Kyoto Protocol: An international treaty created in 1997 in Kyoto, Japan to reduce industrial nation's global emissions of greenhouse gases. Thirty-nine countries listed in Annex B to the Kyoto Protocol indicated agreement at this Third Conference of the Parties (COP) to the UN Climate Change Convention (UNFCCC) to contemplate legally binding quantified emission limitation and reduction commitments. The Kyoto Protocol has not yet been ratified.

Levelized cost: A constant periodic stream of costs that when discounted equals the discounted actual varying stream of periodic costs associated with the installation and operation of a given technological system.

Life cycle analysis (LCA): Evaluation of a technology or technological system including all stages of its production, installation, operation, and decommissioning, and all associated inputs to these stages. May include evaluation of life cycle costs, life cycle emissions, or both, and may be complete (following the above definition), or partial.

Marginal cost: The additional cost incurred by producing one more unit of output.

Market barriers: Conditions that prevent or impede the diffusion of cost-effective technologies or practices.

Market Transformation Program: A program to alter or accelerate the evolution or growth of a market, typically for a new technology, and often by the use of production or other subsidies in the short run that are intended to build future market strength, size, or diversity.

Methane (CH₄): A gas emitted from coal seams, natural wetlands, rice paddies, enteric fermentation (gases emitted by ruminant animals), biomass burning, anaerobic decay or organic wastes in landfill sites, gas drilling and venting, and the activities of termites.

MSW: Municipal solid waste.

OECD: Organization for Economic Cooperation and Development, an organization of mainly free-market industrialized countries setup to assist member states to develop economic and social policies to promote sustained economic growth with financial stability.

Operation and maintenance (O&M) costs: Periodic costs associated with equipment use, including costs of fuel, equipment testing and overhaul, and other periodic inputs.

Ozone (O₃): Tropospheric ozone is oxygen in condensation form in the lowest stratum of the atmosphere, otherwise known as smog.

Particulate matter (PM): A category of air pollutants that refers to small, solid particles or liquid droplets suspended in air.

Photosynthesis: The metabolic process by which plants take CO₂ from the air or water to build plant material, releasing CO₂ in the process.

Photovoltaics: The use of lenses or mirrors to concentrate direct solar radiation onto small areas of solar cells, or the use of flat-plate photovoltaic modules using large arrays of solar cells to convert the sun's radiation into electricity.

Ppm: An abbreviation for parts per million.

Producer-gas: A gas produced from the gasification of biomass which consists primarily of carbon monoxide, hydrogen, carbon dioxide and nitrogen, and has a heating value of 10 – 15 percent of the heating value of natural gas.

Progress ratio (PR): A measure of the rate of improvement in a technology metric, typically cost per unit. Progress ratios are often assessed in terms of percentage reduction per doubling of accumulated production, such that 1-PR is equal to the percentage reduction (e.g., an 85% progress ratio in manufacturing cost indicates a 15% reduction in cost with each doubling of accumulated production).

Sinks: Places where CO₂ can be absorbed – the oceans, soil and detritus and land biota (trees and vegetation).

SO₂: Sulphur dioxide, a chemical found in air pollution.

Solar insolation: Incoming solar radiation.

Solar thermal power systems: Focus sunlight to heat an intermediary fluid, known as heat transfer fluid that then is used to generate steam. The steam is then used in a conventional steam turbine to generate electricity.

Steam-Rankine cycle: Direct combustion of biomass in a boiler to raise steam which is then expanded through a turbine

Sustainable development: Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

Synfuels: Short for synthetic fuels, the industry name for hydrocarbon fuels processed from coal, oil shale, or tar sand so that they resemble liquid petroleum fuels derived from crude oil and natural gas.

Watt (W): A unit of measure of power ($1W = 1J/\text{second}$), which is the amount of work performed per unit of time.

Watt-peak (W_p): Power rating of solar modules and systems measured as the power delivered under standard test conditions.

W_e: Power produced for electricity generation.

Wind farm: A number of electricity generating windmills sited in the same area.

Summary

The potential of renewable energy sources is enormous as they can in principle meet many times the world's energy demand. Renewable energy sources such as biomass, wind, solar, hydropower, and geothermal can provide sustainable energy services, based on the use of routinely available, indigenous resources. A transition to renewables-based energy systems is looking increasingly likely as their costs decline while the price of oil and gas continue to fluctuate. In the past 30 years solar and wind power systems have experienced rapid sales growth, declining capital costs and costs of electricity generated, and have continued to improve their performance characteristics. In fact, fossil fuel and renewable energy prices, and social and environmental costs are heading in opposite directions and the economic and policy mechanisms needed to support the widespread dissemination and sustainable markets for renewable energy systems are rapidly evolving. It is becoming clear that future growth in the energy sector will be primarily in the new regime of renewable energy, and to some extent natural gas-based systems, not in conventional oil and coal sources. Because of these developments market opportunity now exists to both innovate and to take advantage of emerging markets to promote renewable energy technologies, with the additional assistance of governmental and popular sentiment. The development and use of renewable energy sources can enhance diversity in energy supply markets, contribute to securing long term sustainable energy supplies, help reduce local and global atmospheric emissions, and provide commercially attractive options to meet specific energy service needs, particularly in developing countries and rural areas helping to create new employment opportunities there.

1. Introduction

Conventional energy sources based on oil, coal, and natural gas have proven to be highly effective drivers of economic progress, but at the same time damaging to the environment and to human health. Furthermore, they tend to be cyclical in nature, due to the effects of oligopoly in production and distribution. These traditional fossil fuel-based energy sources are facing increasing pressure on a host of environmental fronts, with perhaps the most serious challenge confronting the future use of coal being the Kyoto Protocol greenhouse gas (GHG) reduction targets. It is now clear that any effort to maintain atmospheric levels of CO₂ below even 550 ppm cannot be based fundamentally on an oil and coal-powered global economy, barring radical carbon sequestration efforts.

The potential of renewable energy sources is enormous as they can in principle meet many times the world's energy demand. Renewable energy sources such as biomass, wind, solar, hydropower, and geothermal can provide sustainable energy services, based on the use of routinely available, indigenous resources. A transition to renewables-based energy systems is looking increasingly likely as the costs of solar and wind power systems have dropped substantially in the past 30 years, and continue to decline, while the price of oil and gas continue to fluctuate. In fact, fossil fuel and renewable energy prices, social and environmental costs are heading in opposite directions. Furthermore, the economic and policy mechanisms needed to support the widespread dissemination and sustainable markets for renewable energy systems have also rapidly evolved. It is becoming clear that future growth in the energy sector is primarily in the new regime of renewable, and to some extent natural gas-based systems, and not in conventional oil and coal sources. Financial markets are awakening to the future growth potential of renewable and other new energy technologies, and this is a likely harbinger of the economic reality of truly competitive renewable energy systems.

In addition, renewable energy systems are usually founded on a small-scale, decentralized paradigm that is inherently conducive to, rather than at odds with, many electricity distribution, cogeneration (combined heat and power), environmental, and capital cost issues. As an alternative to custom, onsite construction of centralized power plants, renewable systems based on PV arrays, windmills, biomass or small hydropower, can be mass-produced "energy appliances" capable of being manufactured at low cost and tailored to meet specific energy loads and service conditions. These systems can have dramatically reduced as well as widely dispersed environmental impacts, rather than larger, more centralized impacts that in some cases are serious contributors to ambient air pollution, acid rain, and global climate change.

Renewable energy sources currently supply somewhere between 15 percent and 20 percent of world's total energy demand. The supply is dominated by traditional biomass, mostly fuel wood used for cooking and heating, especially in developing countries in Africa, Asia and Latin America. A major contribution is also obtained from the use of large hydropower; with nearly 20 percent of the global electricity supply being provided by this source. New renewable energy sources (solar energy, wind energy, modern bio-energy, geothermal energy, and small hydropower) are currently contributing about two percent. A number of scenario studies have investigated the potential contribution of renewables to global energy supplies, indicating that in

the second half of the 21st century their contribution might range from the present figure of nearly 20 percent to more than 50 percent with the right policies in place.

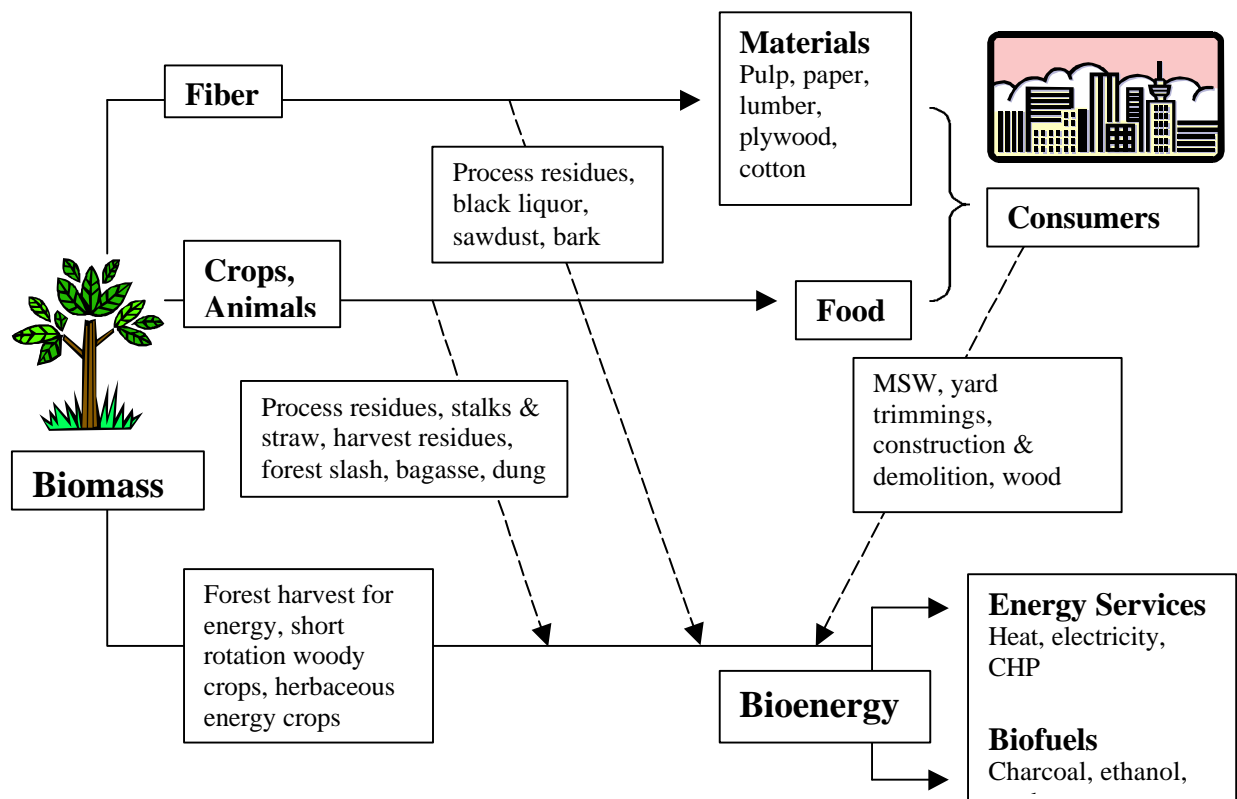
2. Biomass Energy

2.1. Introduction

Biomass is the term used for all organic material originating from plants (including algae), trees and crops and is essentially the collection and storage of the sun's energy through photosynthesis. Biomass energy, or bioenergy, is the conversion of biomass into useful forms of energy such as heat, electricity and liquid fuels.

Biomass for bioenergy comes either directly from the land, as dedicated energy crops, or from residues generated in the processing of crops for food or other products such as pulp and paper from the wood industry. Another important contribution is from post consumer residue streams such as construction and demolition wood, pallets used in transportation, and the clean fraction of municipal solid waste (MSW). The biomass to bioenergy system can be considered as the management of flow of solar generated materials, food, and fiber in our society. These inter-relationships are shown in Figure 1, which presents the various resource types and applications, showing the flow of their harvest and residues to bioenergy applications. Not all biomass is directly used to produce energy but rather it can be converted into intermediate energy carriers called biofuels. This includes charcoal (higher energy density solid fuel), ethanol (liquid fuel), or producer-gas (from gasification of biomass).

Figure 1. Biomass and bioenergy flow chart (Source: R.P. Overend, NREL, 2000)



Biomass was the first energy source harnessed by humans, and for nearly all of human history, wood has been our dominant energy source. Only during the last century, with the development of efficient techniques to extract and burn fossil fuels, have coal, oil, and natural gas, replaced wood as the industrialized world's primary fuel. Today some 40 to 55 exajoules (EJ = 10^{18} joules) per year of biomass is used for energy, out of about 450 EJ per year of total energy use, or an estimated 10-14 percent, making it the fourth largest source of energy behind oil (33 percent), coal (21 percent), and natural gas (19 percent). The precise amount is uncertain because the majority is used non-commercially in developing countries.

Biomass is usually not considered a modern energy source, given the role that it has played, and continues to play, in most developing countries. In developing countries it still accounts for an estimated one third of primary energy use while in the poorest up to 90% of all energy is supplied by biomass. Over two billion people cook by direct combustion of biomass, and such traditional uses typically involve the inefficient use of biomass fuels, largely from low cost sources such as natural forests, which can further contribute to deforestation and environmental degradation. The direct combustion of biomass fuels, as used in developing countries today for domestic cooking and heating, has been called "the poor man's oil" ranking at the bottom of the ladder of preferred energy carriers where gas and electricity are at the top.

The picture of biomass utilization in developing countries is sharply contrasted by that in industrialized countries. On average, biomass accounts for 3 percent or 4 percent of total energy use in the latter, although where policies supportive of biomass use are in place, e.g. in Austria, Sweden, and Finland, the biomass contribution reaches 12, 18, and 23 percent respectively. Most biomass in industrialized countries is converted into electricity and process heat in cogeneration systems (combined heat and power production) at industrial sites or at municipal district heating facilities. This enables a greater variety of energy services to be derived from the biomass which are much cleaner and use the available biomass resources more efficiently than is typical in developing countries.

Biomass energy has the potential to be "modernized" worldwide, that is produced and converted efficiently and cost-competitively into more convenient forms such as gases, liquids, or electricity. A variety of technologies can convert solid biomass into clean, convenient energy carriers over a range of scales from household/village to large industrial. Some of these technologies are commercially available today while others are still in the development and demonstration stages. If widely implemented, such technologies could enable biomass energy to play a much more significant role in the future than it does today, especially in developing countries.

2.2. The Future Role of Biomass

Modernized biomass energy is projected to play a major role in the future global energy supply. This is being driven not so much by the depletion of fossil fuels, which has ceased to be a defining issue with the discovery of new oil and gas reserves and the large existing coal resources, but rather by the recognized threat of global climate change, caused largely by the burning of fossil fuels. Its carbon neutrality (when produced sustainably) and its relatively even geographical distribution coupled with the expected growth in energy demand in developing

countries, where affordable alternatives are not often available, make it a promising energy source in many regions of the world for the 21st century.

Most households in developing countries that use biomass fuels today do so either because it is available at low (or zero) financial cost or because they lack access to or cannot afford higher quality fuels. As incomes rise, preferences tend to shift away from biomass. For example, in the case of cooking, consumer preferences shift with increasing income from dung to crop residues, fuelwood, coal, charcoal, kerosene, liquified petroleum gas, natural gas, and electricity (the well-known household energy ladder). This shift away from biomass energy as incomes rise is associated with the quality of the energy carrier used rather than with the primary energy source itself. If biomass energy is instead modernized, then wider use is conceivable along with benefits such as reduced indoor air pollution. For example, in household cooking gaseous or liquid cooking fuels can be used far more efficiently and conveniently, reaching many more families and emitting far fewer toxic pollutants, than solid fuels.

Estimates of the technical potential of biomass energy are much larger than the present world energy consumption. If agriculture is modernized up to reasonable standards in various regions of the world, several billions of hectares may be available for biomass energy production well into this century. This land would comprise degraded and unproductive lands or excess cropland, and preserve the world's nature areas and quality cropland. Table 1 gives a summary of the potential contribution of biomass to the world's energy supply according to a number of studies and influential organizations. Although the percentile contribution of biomass varies considerably, depending on the expected future energy demand, the absolute potential contributions of biomass in the long term is high, from about 100 to 300 EJ per year.

Table 1. Role of biomass in future global energy use according to five different studies (Source: Hall, 1998; WEA, 2000)

Source	Time frame (Year)	Total projected global energy demand (EJ/year)	Contribution of biomass to energy demand, EJ/year (% of total)	Remarks
IPCC (1996)	2050	560	180 (32%)	Biomass intensive energy system development
	2100	710	325 (46 %)	
Shell (1994)	2060	1500	220 (15%)	- Sustained growth*
		900	200 (22%)	- Dematerialization ⁺
WEC (1994)	2050	671-1057	94 - 157 (14 -15 %)	Range given reflects the outcome of three scenarios
	2100	895-1880	132 - 215 (15-11 %)	
Greenpeace (1993)	2050	610	114 (19 %)	Fossil fuels are phased out during the 21 st century
	2100	986	181 (18 %)	

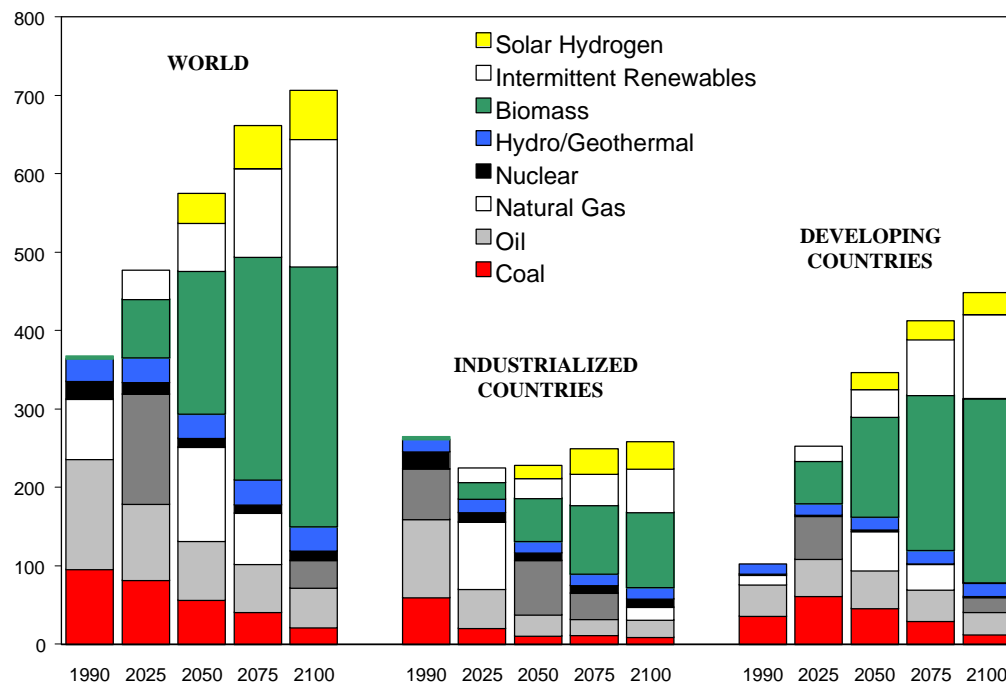
Johansson et al. (1993)	2025	395	145 (37 %)	RIGES model calculation
	2050	561	206 (37 %)	

* *Business-as-usual scenario*

+ *Energy conservation scenario*

An Intergovernmental Panel on Climate Change (IPCC) study has explored five energy supply scenarios for satisfying the world's growing demand for energy services in the 21st century while limiting cumulative CO₂ emissions between 1990 and 2100 to fewer than 500 gigatonnes of carbon. In all scenarios, a substantial contribution from carbon-neutral biomass energy as a fossil fuel substitute is included to help meet the CO₂ emissions targets. When biomass is grown at the same average rate as it is harvested for energy, it is approximately carbon-neutral: carbon dioxide extracted from the atmosphere during growth is released back to the atmosphere during conversion to energy. Figure 2 shows the results for the IPCC's most biomass-intensive scenario where biomass energy contributes 180 EJ/year to global energy supply by 2050 – satisfying about one-third of the total global energy demand, and about half of total energy demand in developing countries. Roughly two-thirds of the global biomass supply in 2050 is assumed to be produced on high-yield energy plantations covering nearly 400 million hectares, or an area equivalent to one-quarter of present planted agricultural area. The other one-third comes from residues produced by agricultural and industrial activities.

Figure 2. Primary commercial energy use by source for the biomass-intensive variant of the IPCC model (IPCC, 1996), shown for the world, for industrialized countries, and for developing countries (Source: Sivan, 2000)



Such large contributions of biomass to the energy supply might help address the global environmental threat of climate change, but it also raises concerns about local and regional

environmental and socio-economic impacts. Such issues (discussed in more detail below) include the: depletion of soil nutrients from crop land due to the removal of agricultural residues; leaching of chemicals applied to intensively-cultivated biomass energy crops; loss of biodiversity associated with land conversion to energy crops; diversion to energy uses of biomass resources traditionally used for non-energy purposes, or conversion of land from food to energy production. Bioenergy systems, more so than most other types of energy systems, are inextricably linked to their local environmental and socio-economic contexts.

On the other hand, the large role biomass is expected to play in future energy supplies can be explained by several considerations. Firstly, biomass fuels can substitute more-or-less directly for fossil fuels in the existing energy supply infrastructure. Intermittent renewables such as wind and solar energy are more challenging to the ways we distribute and consume energy. Secondly, the potential resource is large. Thirdly, in developing countries demand for energy is rising rapidly due to population increases, urbanization, and rising living standards. While some fuel switching occurs in the process, the total demand for biomass will also tend to increase, as is currently seen for charcoal. Consequently, there is a growing consensus that energy policies will need to be concerned about the supply and use of biofuels while supporting ways to use these fuels more efficiently and sustainably.

2.3. Biomass Energy Conversion Technologies and Applications

There are a variety of technologies for generating modern energy carriers – electricity, gas, and liquid fuels -- from biomass, which can be used at the household (~10 kW), community (~100 kW), or industrial (~ MW) scale. The different technologies tend to be classed in terms of either the conversion process they use or the end product produced.

2.3.1 Combustion

Direct combustion remains the most common technique for deriving energy from biomass for both heat and electricity production. In colder climates domestic biomass fired heating systems are widespread and recent developments have led to the application of improved heating systems which are automated, have catalytic gas cleaning and make use of standardized fuel (such as pellets). The efficiency benefit compared to open fireplaces is considerable with advanced domestic heaters obtaining efficiencies of over 70 percent with greatly reduced atmospheric emissions. The application of biomass fired district heating is common in the Scandinavian countries, Austria, Germany and various Eastern European countries.

The predominant technology in the world today for electricity generation from biomass, at scales above one megawatt, is the steam-Rankine cycle. This consists of direct combustion of biomass in a boiler to raise steam which is then expanded through a turbine. The steam-Rankine technology is a mature technology introduced into commercial use about 100 years ago. The typical capacity of existing biomass power plants ranges from 1 – 50 MW_e with an average around 20 MW_e. Energy conversion efficiencies are relatively low, 15 – 25 percent, due to their small size, although technologies and processes to increase these efficiencies are being developed. Steam cycle plants are often located at industrial sites, where the waste heat from the steam turbine is recovered and used for meeting industrial process heat needs. Such combined

heat and power (CHP), or cogeneration, systems provide greater levels of energy services per unit of biomass consumed than systems that only generate power and can reach overall efficiencies of greater than 80 percent.

Biomass power generating capacity grew rapidly in the US in the 1980s largely as the result of incentives provided by the Public Utilities Regulatory Policies Act of 1978 (PURPA), which required utilities to purchase electricity from cogenerators and other qualifying independent power producers at a price equal to the utilities' avoided costs. Currently in the U.S. the installed biomass-electric generating capacity is about 7 GW (not including generating capacity of ~ 2.5 GW from MSW and ~ 0.5 GW from landfill gas). The majority of this capacity is located at pulp and paper mills, where biomass fuels are available as byproducts of processing. There are also a substantial number of biomass power plants in California that use agricultural processing wastes as fuel. A significant number of biomass power plants are also found in Scandinavia, especially Sweden, where carbon taxes have encouraged recent expanded use of such systems for combined district heating and power production. By comparison to the steam-Rankine power generating capacity installed in OECD countries, there is relatively little capacity installed in developing countries. The most significant installation of steam-Rankine capacity in developing countries is at factories making sugar and/or ethanol from sugarcane, using bagasse, the fiber residue that remains after juice extraction from sugarcane.

The costs of steam-Rankine systems vary widely depending on the type of turbine, type of boiler, the pressure and temperature of the steam, and other factors. An important characteristic of steam turbines and boilers is that their capital costs (per unit of capacity) are scale-sensitive. This, together with the fact that biomass steam-Rankine systems are constrained to relatively small scales (due to biomass fuel transport cost limitations), typically leads to biomass steam-Rankine systems that are designed to reduce capital costs at the expense of efficiency. For example, biomass-fired systems are typically designed with much more modest steam pressure and temperature than is technologically feasible enabling lower grade steels to be used in boiler tubes. This lowers both the costs and efficiency. Even with such measures to reduce costs, however, capital costs for small-scale systems are still substantial and lead to relatively high electricity generating costs compared to conventional fossil energy power plants. Consequently, existing biomass power plants rely on low, zero, or negative cost biomass, such as primarily residues of agro- and forest product-industry operations. Since there are untapped supplies of low-cost biomass feedstocks available in many regions of the world the economics of steam-Rankine systems are probably reasonable. For example, sugarcane processing industries and sawmills present major opportunities for steam-Rankine based combined heat and power generation from biomass.

An alternative to the above-described direct-fired biomass combustion technologies, and considered the nearest term low-cost option, is biomass co-combustion with fossil fuels in existing boilers. Successful demonstrations using biomass as a supplementary energy source in large high efficiency boilers have been carried out showing that effective biomass fuel substitution can be made in the range of 10–15 percent of the total energy input with minimal plant modifications and no impact on the plant efficiency and operation. This strategy is economical when the biomass fuels are lower cost than the fossil fuels used. For fossil fuel plant

capacities greater than 100 MW_e, this can mean a substantial amount of biomass and related carbon savings and emissions reductions, particularly for coal substitution.

2.3.2. Gasification

Combustible gas can be produced from biomass through a high temperature thermochemical process. The term gasification commonly refers to this high-temperature thermochemical conversion with the product gas called producer-gas, and involves burning biomass without sufficient air for full combustion, but with enough air to convert the solid biomass into a gaseous fuel. Producer-gas consists primarily of carbon monoxide, hydrogen, carbon dioxide and nitrogen, and has a heating value of 4 to 6 MJ/Nm³, or 10 – 15 percent of the heating value of natural gas. The intended use of the gas and the characteristics of the particular biomass (size, texture, moisture content, etc.) determine the design and operating characteristics of the gasifier and associated equipment. After appropriate treatment, the resulting gases can be burned directly for cooking or heat supply, or can be used in secondary conversion devices such as internal combustion engines or gas turbines for producing electricity or shaft work. The systems used can scale from small to medium (5 –100 kW), suitable for the cooking or lighting needs of a single family or community, up to large grid connected power generation facilities consuming several hundred of kilograms of woody biomass per hour and producing 10-100 MW of electricity.

After the first oil price shock in 1973 crash attempts were made to resurrect and install gasifier/engine systems for electricity generation, especially in remote areas of developing countries. Most of these projects failed, however, because of technical problems arising from the formation of tars and oils (heavy hydrocarbon compounds) during gasification. Condensation of tars on downstream equipment caused system operating problems and failures. Such problems were encountered in many of the gasifier/engine systems installed in the 1970s and 1980s, and led to a second abandonment of gasifier/engine technology by the end of the 1980s. Research efforts continued, however, and have recently led to the identification of gasifier and gas cleanup system designs that largely eliminate tar production and other technical problems, although they tend to still be too expensive. The process of transferring these research findings into commercial products is ongoing, as interest in gasification has again revived with the growing recognition of environmental concerns. One of the main barriers to commercializing biopower technology continues to be the low cost of oil, gas and coal.

One technology that has generated wide interest is the biomass integrated gasification combined cycle (IGCC) technology for larger scale power and combined heat and power (CHP) generation in the range of 5 to 100 MW_e. An IGCC system involves sizing and drying of the feedstock, followed by thermochemical gasification to produce a combustible gas, cooling and cleaning of the gas, and combustion in a gas turbine. Steam is raised using the hot exhaust of the gas turbine to drive a steam turbine that generates additional power and/or delivers lower pressure steam for heating purposes. The cascading of a gas turbine and a steam turbine in this manner is commonly called a combined cycle. In approximate terms, the IGCC technology will enable electricity to be made at double or more the efficiency of the steam cycle, and the capital cost per installed kW for commercially mature IGCC units are expected to be lower than for comparably-sized steam cycles. Thus, the overall economics of biomass-based power generation are expected to be

considerably better with an IGCC system than with a steam-Rankine system, especially in situations where biomass fuel is relatively expensive.

IGCC technology is expected to be commercially available within a few years, based on current demonstration and commercialization efforts worldwide. Several of the most advanced demonstration projects are in Sweden, the UK, Italy, and Brazil. In Varnamo, Sweden, the first complete biomass fueled IGCC system has been operating for over 1500 hours on forest residues, generating 6 MW of electricity and 9 MW of heat for the local district heating system. Unfortunately, it was recently shut down probably due its inability to compete economically with fossil fuel systems. In Yorkshire, England, construction of the ARBRE project, an IGCC facility that will generate about 10 MW of electricity from short-rotation biomass plantations, is nearly complete. It is supported under both THERMIE and the U.K.'s Non-Fossil Fuel Obligation-3. The Bioelettrica Project near Pisa, Italy, an IGCC, is also under construction and will use Poplar and Robina wood chips, olive residues, grape residues, and sawdust to produce 12 MW_e. At a site in Bahia, Brazil, construction is planned to begin in 2000 on a GEF-World Bank supported demonstration project of a 32 MW IGCC power plant using plantation-grown eucalyptus for fuel. The facility will also test the use of sugarcane bagasse. It has been estimated that if IGCC technology was applied worldwide around 25 % of all current electricity generation from sugarcane producing countries could be produced just from their available sugarcane bagasse resource.

At the intermediate scale producer-gas from biomass gasification can be used in modified internal combustion engines (typically diesel engines), where it can replace 70-80 percent of the conventional fuel required by the engine. These smaller scale biomass gasifiers, coupled to diesel/gas internal combustion engines, operate in the 100-200 kW_e range with efficiencies on the order of 15 – 25 percent, and have been made available commercially. They have, however, had only limited operation success due to, gas cleaning, relatively high costs and the required careful operation, which has so far blocked application in large numbers. Thus, practical operation has often been limited to direct heating applications and not electricity where gas cleanup and its associated problems become an issue.

Generally, these smaller gasification/engine systems are targeted toward isolated areas where grid-connections are either unavailable or unreliable and so they can be cost competitive in generating electricity. Some systems have been applied relatively successfully in rural India and some other countries. Efforts to make these systems more workable are underway. In particular, the U.S. National Renewable Energy Laboratory is funding a small modular biopower project to develop biomass systems that are fuel flexible, efficient, simple to operate, have minimum negative impacts on the environment, and provide power in the 5 kW - 5 MW range. This is a three-phase project (feasibility studies, prototype testing, integrated systems demonstration) currently beginning its second phase. There is particularly strong interest in the quality-of-life improvements that can be derived from implementing such gasifier/engine technology for electricity generation at the village-scale in developing countries.

The greatest technical challenge for electricity generating gasifier systems, at all scales, continues to be adequately cleaning the tars and oils from the producer-gas such that the system operates efficiently, is economical, and has minimal toxic byproducts and air emissions.

2.3.3. Anaerobic Digestion

Combustible gas can also be produced from biomass through the low temperature biological processes called anaerobic (without air) digestion. Biogas is the common name for the gas produced either in specifically designed anaerobic digesters or in landfills by capturing the naturally produced methane. Biogas is typically about 60 percent methane and 40 percent carbon dioxide with a heating value of about 55 percent that of natural gas. Almost any biomass except lignin (a major component of wood) can be converted to biogas -- animal and human wastes, sewage sludge, crop residues, carbon-laden industrial processing byproducts, and landfill material have all been widely used.

Anaerobic digesters generally consist of an inlet, where the organic residues and other wastes are fed into the digester tank; a tank, in which the biomass is typically heated to increase its decomposition rate and partially convert by bacteria into biogas; and an outlet where the biomass of the bacteria that carried out the process and non-digested material remains as sludge and can be removed. The biogas produced can be burned to provide energy for cooking and space heating or to generate electricity. Digestion has a low overall electrical efficiency (roughly 10-15 percent, strongly dependent on the feedstock) and is particularly suited for wet biomass materials. Direct non-energy benefits are especially significant in this process. The effluent sludge from the digester is a concentrated nitrogen fertilizer and the pathogens in the waste are reduced or eliminated by the warm temperatures in the digester tank.

Anaerobic digestion of biomass has been demonstrated and applied commercially with success in a multitude of situations and countries. In India biogas production from manure and wastes is applied widely in many villages and is used for cooking and power generation. Small-scale digesters have been used most extensively in India and China. Over 1.85 million cattle-dung digesters were installed in India by the mid-1990s, but about one-third of these are not operating for a variety of reasons, primarily insufficient dung supply and difficulties with the organization of dung deliveries. A mass popularization effort in China in the 1970s led to some 7 million household-scale digesters being installed, using pig manure and human waste as feed material. Many failed to work, however, due to insufficient or improper feed characteristics or poor construction and repair techniques. Estimates were that some 3 to 4.5 million digesters were operating in the early 1980s. Since then, research, development, and dissemination activities have focused greater attention on proper construction, operation, and maintenance of digesters. One estimate is that there were some 5 million household digesters in working condition in China as of the mid 1990s. There are in addition some 500 large-scale digesters operating at large pig farms and other agro-industrial sites, and some 24,000 digesters at urban sewage treatment plants.

Several thousand biogas digesters are also operating in other developing countries, most notably South Korea, Brazil, Thailand and Nepal. In addition, there are an estimated 5000 digesters installed in industrialized countries, primarily at large livestock processing facilities (stockyards) and municipal sewage treatment plants. An increasing number of digesters are located at food processing plants and other industrial facilities. Most industrial and municipal digesters are used predominantly for the environmental benefits they provide, rather than for fuel production.

2.3.4. Liquid Biofuels

Biofuels are produced in processes that convert biomass into more useful intermediate forms of energy. There is particular interest in converting solid biomass into liquids, which have the potential to replace petroleum-based fuels used in the transportation sector. However, adapting liquid biofuels to our present day fuel infrastructure and engine technology has proven to be non-trivial. Only oil producing plants, such as soybeans, palm oil trees and oilseeds like rapeseed can produce compounds similar to hydrocarbon petroleum products, and have been used to replace small amounts of diesel. This “biodiesel” has been marketed in Europe and to a lesser extent in the U.S., but it requires substantial subsidies to compete with diesel. Another family of petroleum-like liquid fuels that is produced from gasified biomass is a class of synthesized hydrocarbons called Fischer-Tropsch (F - T) liquids. The process synthesizes hydrocarbon fuels (C_{10} - C_{12} hydrocarbons (kerosene) or C_3 - C_4 hydrocarbons (LPG)) from carbon monoxide and hydrogen gas over iron or cobalt catalysts. F - T liquids can be used as a sulfur-free diesel or blended with existing diesel to reduce emissions, an environmental advantage, but it has yet to be produced efficiently and economically on a large scale, and research and development (R&D) efforts are ongoing. In addition, to use as an automotive fuels F-T liquids can potentially be used as a more efficient, cleaner cooking fuel than traditional wood fuels from which it is synthesized.

Other alternative biofuels to petroleum-based fuels are alcohols produced from biomass, which can replace gasoline or kerosene. The most widely produced today is ethanol from the fermentation of biomass. In industrialized countries ethanol is most commonly produced from food crops like corn, while in the developing world it is produced from sugarcane. Its most prevalent use is as a gasoline fuel additive to boost octane levels or to reduce dependence on imported fossil fuels. In the U.S. and Europe the ethanol production is still far from competitive when compared to gasoline and diesel prices, and the overall energy balance of such systems has not been very favorable. The Brazilian Proalcool ethanol program, initiated in 1975, has been successful due to the high productivity of sugarcane, although subsidies are still required. Two other potential transportation biofuels are methanol and hydrogen. They are both produced via biomass gasification and may be used in future fuel cells.

While ethanol production from maize and sugarcane, both agricultural crops, has become widespread and occasionally successful it can suffer from commodity price fluctuation relative to the fuels market. Consequently, the production of ethanol from lignocellulosic biomass (such as wood, straw and grasses) is being given serious attention. In particular, it is thought that enzymatic hydrolysis of lignocellulosic biomass will open the way to low cost and efficient production of ethanol. While the development of various hydrolysis techniques has gained attention in recent years, particularly in Sweden and the United States, cheap and efficient hydrolysis processes are still under development and some fundamental issues need to be resolved. Once such technical barriers are surmounted and ethanol production can be combined with efficient electricity production from unconverted wood fractions (like the lignine), ethanol costs could come close to current gasoline prices and overall system efficiencies could go up to about 70 percent (low heating value). Though the technology to make this an economically viable option still does not exist, promising technologies are in the works and there are currently a number of pilot and demonstration projects starting up.

2.4. Implementation of Biomass Energy Systems

Raw biomass has several disadvantages as an energy source. It is bulky with a low energy density and direct combustion is generally highly inefficient (other than advanced domestic heaters) producing high levels of indoor and outdoor air pollution. The goal of modernized biomass energy is to increase the fuel's energy density while decreasing its emissions during production and use. Modernizing biomass energy production however faces a variety of challenges that must be adequately addressed and dealt with before the widespread implementation of bioenergy systems can occur. These issues include technical problems (just discussed), resource availability, environmental impacts, and economic feasibility.

2.4.1 Biomass Resources

Biomass resources are potentially the largest renewable global energy source, with an annual primary production of around 4500 EJ with a bioenergy potential on the order of 2900 EJ, of which about 270 EJ could be considered available on a sustainable basis. The challenge is not the availability so much as the sustainable management and conversion and delivery to the consumer in the form of modern and affordable energy services. Most of the biomass used today is either a residue in a bioprocessing industry or is an opportunity fuel that is used in households for daily living needs. It is argued that if biomass is to become a major fuel in the world, as is being proposed in future energy scenarios, then residues will not suffice and energy plantations may need to supply up to 80 percent of the future feedstock.

The solar energy conversion efficiency of plants is low, in practice less than 1 percent. Consequently relatively large land surfaces are required to produce a substantial amount of energy. Moreover biomass has a low energy density. For comparison: coal has an energy density of 28 GJ/ton, mineral oil of 42 GJ/ton, liquified natural gas of 52 GJ/ton while biomass is only 8 GJ/ton of wood (50 percent moisture content). Consequently transportation becomes an essential element of biomass energy systems, with transportation distances becoming a limiting factor, both from an economic and energetic point of view. While generally it has been found that for woody biomass the energy output is 10-30 times greater than the energy input necessary for fuel production and transport, the issue is less clear for the production of liquid fuels, except ethanol from sugarcane, which does have high net energy yields.

At present the production of biomass residues and wastes globally, including byproducts of food, fiber and forest production exceeds 110 EJ/year, perhaps 10 percent of which is used for energy. Residues concentrated at industrial sites are currently the largest commercially used biomass source. Residues are not, however, always accessible for energy use. In some cases collection and transport costs are prohibitive; in other cases, agronomic considerations dictate that residues be recycled to the land. In still other cases, there are competing non-energy uses for residues (e.g., fodder, construction material, industrial feedstock, etc.).

Residues are an especially important potential biomass energy source in densely populated regions, where much of the land is used for food production. In fact, biomass residues play important roles in such regions precisely because the regions produce so much food: crop production can generate large quantities of byproduct residues. For example, in 1996 China generated crop residues in the field (mostly corn stover, rice straw, and wheat straw) plus agricultural processing residues (mostly rice husks, corn cobs, and bagasse) totaling about 790

million tonnes, with a corresponding energy content of about 11 EJ. To put this in perspective, if half of this resource were to be used for generating electricity at an efficiency of 25 percent (achievable at small scales today), the resulting electricity generation would be about half of the total electricity generated from coal in China in 1996.

There is also a significant potential for providing biomass for energy by growing crops specifically for that purpose. The IPCC's biomass intensive future energy supply scenario discussed previously includes 385 million hectares of biomass energy plantations globally in 2050 (equivalent to about one-quarter of present planted agricultural area), with three-quarters of this area established in developing countries. Such levels of land use for bioenergy raises the issue of intensified competition with other important land uses, especially food production. Competition between land use for agriculture and for energy production can be minimized if degraded land and surplus agricultural land are targeted for energy crops. In developing countries in aggregate there are about 2 billion hectares of land that have been classified as degraded. While there are many technical, socioeconomic, political, and other challenges involved in successfully growing energy crops on degraded lands, the feasibility of overcoming such challenges is demonstrated by the fact that successful plantations have already been established on degraded lands in developing countries.

There are two approaches to producing energy crops. These include devoting an area exclusively to production of such crops, and co-mingling the production of energy and non-energy crops, either on the same piece of land (agro-forestry) or on adjacent pieces of land (farm forestry). Since energy crops typically require several years to grow before the first harvest, the second approach has the benefit of providing the energy-crop farmer with revenue from the land between harvests of energy crops. In Sweden productive heat power generation from willow plantations has been successful, and there has also been experience in small-scale fuelwood production in India, China, and elsewhere. While in Brazil farm forestry activities have involved small farmers in the high-yield production of biomass feedstocks.

2.4.2. Environmental Impacts and Benefits

In general renewable forms of energy are considered “green” because they cause little depletion of the Earth’s resources, have beneficial environmental impacts, and cause negligible emissions during power generation. Yet, while biomass is in principle renewable and can have positive environmental impacts if managed properly it also shares many characteristics with fossil fuels, both good and bad. While it can be transported and stored allowing for heat and power generation on demand, modernized bioenergy systems can also have negative environmental impacts associated both with the growing of the biomass and with its conversion to energy carriers.

Environmental impacts of biomass production must be viewed in comparison to the likely alternative impacts (locally, regionally, and globally) without the bioenergy system in place. For example, at the local or regional level, the relative impacts of producing bioenergy feedstocks will depend not only on how the biomass is produced, but also on what would have happened otherwise. Through life cycle analysis (LCA) studies it has been found that where biomass displaces fossil energy systems there will be a reduction in the impact on global climate through

a reduction in overall greenhouse gas emissions, but for other types of emissions (i.e., NO_x, SO₂, N₂O) the picture is less clear and is strongly dependent on the source of the biomass, technical details of the conversion process, and the fossil fuel being displaced.

Many bioenergy conversion technologies offer flexibility in choice of feedstock and the manner in which it is produced. In contrast, most agricultural products are subject to rigorous consumer demands in terms of taste, nutritional content, uniformity, etc. This flexibility makes it easier to meet the simultaneous challenges of producing biomass energy feedstocks and meeting environmental objectives. For example, unlike the case with food crops, there are good possibilities for bioenergy crops to be used to revegetate barren land, to reclaim water logged or salinated soils, and to stabilize erosion-prone land. Biomass energy feedstocks when properly managed can both provide habitat and improve biodiversity on previously degraded land.

Erosion and removal of soil nutrients are problems related to the cultivation of annual crops in many regions of the world. While relative to a healthy natural ecosystem bioenergy systems may increase erosion and deplete soil nutrients and quality, bioenergy production on degraded or erosion-prone lands can instead help stabilize soils, improve their fertility, and reduce erosion. Perennial energy crops (unlike food crops) improve land cover and form an extensive root system adding to the organic matter content of the soil. Also removal of soil during energy crop harvest can be kept to a minimum since roots are left in place, and twigs and leaves can be left to decompose in the field enhancing the soil's nutrients. This helps prevent diseases and improve the soil fertility and quality. Environmental benefits of biomass crops, for carbon sequestration, biodiversity, landscape and soil stabilization can be particularly significant if plantations are established on intensively managed agricultural land. While energy crops can be harvested by coppicing every few years (three or four) the stools (rootstocks) can survive for many decades, or even centuries becoming significant carbon sinks. In addition, there are considerable benefits for both landscape and biodiversity when native species are used. For example in Europe it would be preferable to grow willows and poplars rather than eucalyptus. Willows in particular support a high biomass and diversity of phytophagous insects, which in turn can support an important food web with many bird species. Also when feasible the recycling of ashes from the biomass combustion can return crucial trace elements and phosphates to the soil. This is already common practice in countries like Sweden and Austria where part of the ashes are returned to the forest floors, and in Brazil, where stillage, a nutrient rich remainder of sugar cane fermentation, is returned to sugar cane plantations.

Another important potential impact from bioenergy feedstock production is the introduction of agricultural inputs into the environment such as fertilizers and pesticides. Fertilizers and the use of pesticides can adversely affect the health of people, water quality, and plant and animal life. Specific effects strongly depend on the type of chemical, the quantities used and the method of application. Current experience with perennial crops (like Willow, Poplar or Eucalyptus) suggests that those crops meet very strict environmental standards. Compared to food crops like cereals application rates of agrochemicals per hectare are a factor 5-20 lower for perennial energy crops. The abundant use of fertilizers and manure in agriculture has led to considerable environmental problems in various regions in the world: nitrification of groundwater, saturation of soils with phosphate, leading to eutrophication and problems in meeting drinking water standards. Also, the application of phosphates has led to increased heavy metal flux to the soil.

Energy farming with short rotation forestry and perennial grasses, however, requires less fertilizer than conventional agriculture. With perennials better recycling of nutrients is obtained. The leaching of nitrogen relating to Willow cultivation can be about a factor of 2-10 less than for food crops and is able to meet stringent standards for groundwater protection.

Possibly the biggest concern, and often considered the most limiting factor to the spread of bioenergy crops, is the demand on available water supplies, particularly in (semi-) arid regions. The choice of a certain energy crop can have a considerable effect on its water-use efficiency. Certain Eucalyptus species for example have very good water-use efficiency when the amount of water needed per ton of biomass produced is considered. But a Eucalyptus plantation on a large area could increase the local demand for ground water and effect groundwater level. On the other hand, energy crops on previously degraded land will improve land cover, which generally has positive effects on water retention and micro-climate conditions. Impacts on the hydrological situation therefore always need to be evaluated on local level.

Finally, there is the issue of biodiversity and landscape. Biomass plantations are frequently criticized because the range of biological species they support is much narrower than natural ecosystems. While generally true, this is not always relevant. It would be if a virgin forest were to be replaced by a biomass plantation -- a situation which would be undesirable. However, when plantations are established on degraded lands or on excess agricultural lands as is intended to be the case, the restored lands are very likely to support a more diverse ecology compared to the original situation. The restoration of such land is generally desirable for purposes of water retention, erosion prevention and (micro-) climate control. Furthermore, a good plantation design, including areas set aside for native flora and fauna, fitting into the landscape in a natural way can avoid the problems normally associated with monocultures. The presence of natural predators (e.g. insects) can prevent the outbreak of pests and diseases. This issue needs more research where specific local conditions, species, and cultural aspects are taken into account.

In addition to the environmental concerns of land and water quality from biomass production there are also strict air quality standards that must be met during biomass to energy conversion processes. Luckily, air emissions can be counteracted with relatively well-understood and largely available technology much of which has been developed and implemented in the fossil fuels industry. Unfortunately, it is expensive to implement in some cases. For example, although the technology to meet strict emission standards is available for small (less than 1 MW) conversion systems, it still can have a serious impact on the investment and operational costs of these systems.

2.4.3. Economic and Production Issues

A number of key areas can be identified which are essential for the successful development and implementation of sustainable, economically competitive bioenergy systems.

The main barrier is whether the energy carriers produced are competitive. This is particularly true when specially produced biomass is used. In many situations where cheap or negative cost biomass wastes and residues are available, the utilization of biomass is or could be competitive and future technology development should help further reduce the costs of bioenergy. In Sweden

and Denmark, where a carbon and energy tax has been introduced, more expensive wood fuels and straw are now being used on a large scale. However, on a worldwide basis, the commercial production of energy crops is almost non-existent. Brazil is a major exception where subsidies have been introduced to make ethanol from sugarcane competitive with gasoline.

Closely related to the cost issue are the availability and the full-scale demonstration of advanced conversion technology that combines a high efficiency and an environmentally sound performance with low investment costs. This is essential for competition with fossil fuels when relatively high-cost energy crops are used as energy sources. Advances in the combustion and co-combustion of biomass can considerably increase the attractiveness of combustion as a conversion technology. However, the development and the application of the IGCC technology has the potential to attain higher conversion efficiency at lower costs. Demonstration and commercialization of this technology are therefore important.

Experience with dedicated fuel supply systems based on ‘new’ energy crops like perennial grasses and short rotation crops (SRC) are very limited compared to the experience of cultivating traditional food crops and forestry techniques. Improvement of yields, increased pest resistance, management techniques, reduction of inputs and further development of machinery are all necessary to lower costs and raise productivity. The same is true for harvesting, storage and supply logistics. Bioenergy systems are complex in terms of organization and the number of actors that can be involved in a total energy system. The biomass is most likely to be produced by farmers or foresters while transport and storage are likely to be the responsibility of another party, and utilities may be responsible for the energy production. The combination of the utilities on the one hand and the agricultural system on the other will create a number of non-technical barriers that have to be dealt with for any future system to work.

The externalities of bioenergy, which are not accounted for in its cost, are important to consider as well and can offer benefits compared to fossil fuels. Its carbon neutral character is one of those externalities. Furthermore, biomass has a very low sulfur content. Another aspect is that biomass is available to most countries, while fossil fuels need to be imported from a limited number of suppliers. Indigenous production of energy has macro-economic as well as employment benefits. Biomass production systems can offer relatively large numbers of unskilled jobs, which can be important for many developing countries. Although there are environmental impacts related to bioenergy (as discussed in the previous section) it is usually considerably more beneficial in terms of external costs than coal, gas, and oil.

Countries where commercialized bioenergy applications have started to play a significant role in the energy system have all implemented strong policies. A carbon tax, price support, long running R&D programs can lead to a powerful combination of gaining experience, building an infrastructure, developing technology and at the same time developing the national market. The Scandinavian countries, Brazil and to a somewhat lesser extent Northwest Europe and the U.S., show that “modernization” is essential to realize the promise of biomass as an alternative energy source. Modernization requires environmentally friendly and sustainable high yield biomass production, efficient conversion to clean energy carriers, and efficient end use.

2.5. Conclusions

Biomass is one of the renewable energy sources that is capable of making a large contribution to the world's future energy supply. Land availability for biomass production should not be a bottleneck, provided it is combined with modernization of conventional agricultural production. Recent evaluations indicate that even if land surfaces of 400-700 million hectares were used for biomass production for energy about halfway the next century, this could be done without conflicting with other land-use functions and nature preservation. Partially this can be obtained by better agricultural practices, partially by making use of huge areas of unproductive degraded lands. Latin America, Africa, Asia and to a lesser extent Eastern Europe and North America represent a large potential for biomass production.

The forms in which biomass can be used for energy are diverse and optimal resources, technologies and entire systems will be shaped by local conditions, both physical and socio-economic. Perennial crops in particular may offer cheap and productive biomass production systems with low or positive environmental impacts. Technical improvement and optimized production systems along with multifunctional land-use could bring biomass close to the costs of fossil fuels.

A key issue for bioenergy is that its use must be modernized to fit into a sustainable development. Conversion of biomass to energy carriers like electricity and transportation fuels will give biomass a commercial value and provide income for local rural economies. In order to obtain such a situation it is essential that biomass markets and necessary infrastructure are built up, key conversion technologies like IGCC technology and advanced fuel production systems for methanol, hydrogen and ethanol are demonstrated and commercialized, and that much more experience is gained with biomass production systems in a wide variety of contexts. Although the actual role of bioenergy will depend on its competitiveness versus fossil fuels and agricultural policies, it seems realistic to expect that the current contribution of bioenergy will increase during this century.

3. Wind Energy

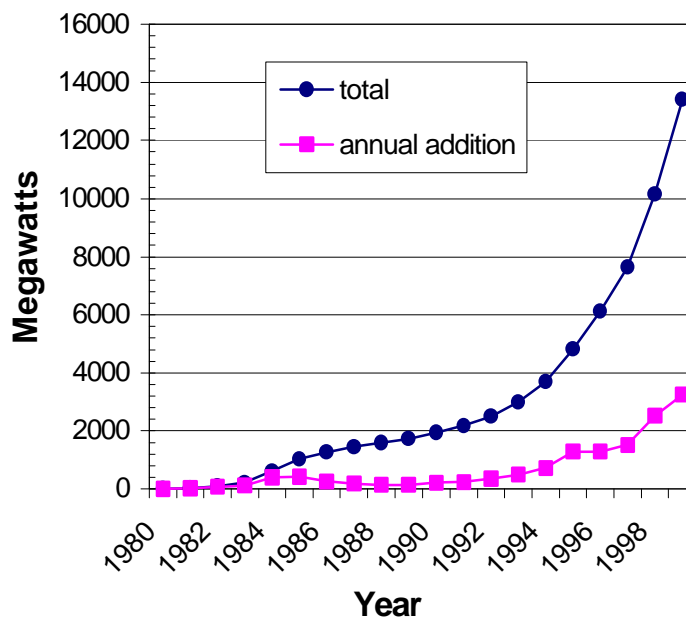
3.1. Introduction

Wind has considerable potential as a global clean energy source, being both widely available, though diffuse, and producing no pollution during power generation. Wind energy has been one of humanity's primary energy sources for transporting goods, milling grain, and pumping water for several millennia. From windmills used in China, India and Persia over 2000 years ago to the generation of electricity in the early 20th century in Europe and North America wind energy has played an important part in our recorded history. As industrialization took place in Europe and then in America, wind power generation declined, first gradually as the use of petroleum and coal, both cheaper and more reliable energy sources, became widespread, and then more sharply as power transmission lines were extended into most rural areas of industrialized countries. The oil crises of the 70's, however, triggered renewed interest in wind energy technology for grid-connected electricity production, water pumping, and power supply in remote areas, promoting the industry's rebirth.

This impetus prompted countries; notably Denmark and the United States, to establish government research and development (R&D) programs to improve wind turbine technology. In conjunction with private industry research this led to a reemergence in the 1980's of wind energy in the United States and Europe, when the first modern grid-connected wind turbines were installed. In the 1990's this development accelerated, with wind becoming the fastest growing energy technology in the world developing into a commercially competitive global power generation industry. While in 1990 only about 2000 MW of grid-connected wind power was in operation worldwide by 1999 this figure had surpassed 10,000 MW, not including the over one million water-pumping wind turbines located in remote areas.

Since 1990 the average annual growth rate in world wind generating capacity has been 24 percent, with rates of over 30 percent in the last two years. Today there is more than 13,000 MW of installed wind power, double the capacity that was in place just three years earlier (Figure 3). This dramatic growth rate in wind power has created one of the most rapidly expanding industries in the world, with sales of roughly \$2 billion in 1998, and predictions of tenfold growth over the next decade. Most 2000 forecasts for installed capacity are being quickly eclipsed with wind power having already passed the 10,000 MW mark in early 1999.

Figure 3. World wind generating capacity, total and annual additions (Source: Worldwatch Institute, 1999)



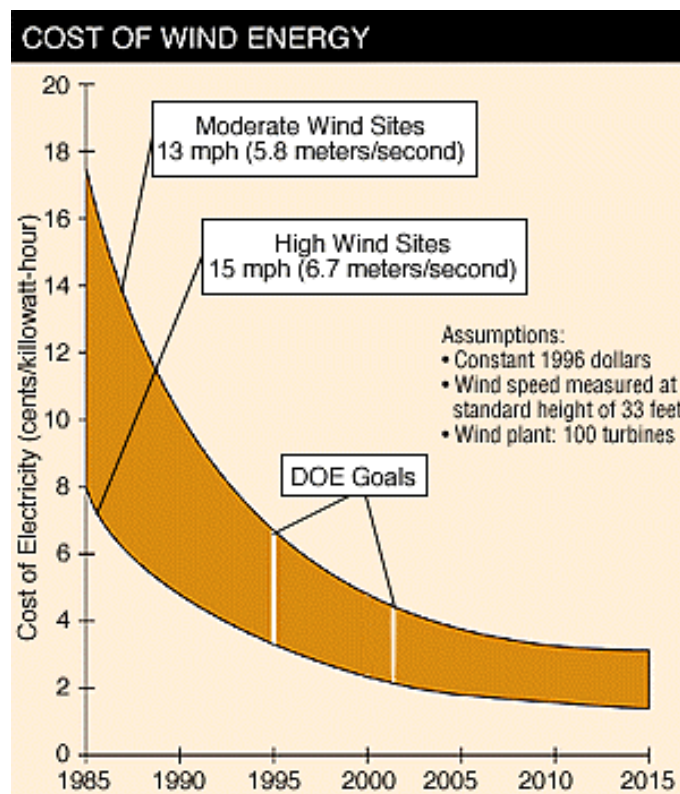
3.2. Economics of Wind Energy

Larger turbines, more efficient manufacturing, and careful siting of wind machines have brought wind power costs down precipitously from \$2600 per kilowatt in 1981 to \$800 per kilowatt in 1998. New wind farms in some areas have now reached economic parity with new coal-based power plants. And as the technology continues to improve, further cost declines are projected,

which could make wind power the most economical source of electricity in some countries. Market growth, particularly in Europe, has been stimulated by a combination of favorable governmental policies, lower costs, improved technology (compared to wind turbines built in 1981, modern turbines generate 56 times the energy at only 9 times the cost), and concern over environmental impacts of energy use.

Wind energy is currently one of the most cost-competitive renewable energy technologies. Worldwide, the cost of generating electricity from wind has fallen by more than 80 percent, from about 38 US cents in the early 1980s to a current range of 3-6 US cents/kWh levelized over a plant's lifetime, and analysts forecast that costs will drop an additional 20-30 percent in the next five years. Consequently, in the not-too-distant future, analysts believe, wind energy costs could fall lower than most conventional fossil fuel generators, reaching a cost of 2.5 US cents/kWh (Figure 4).

Figure 4. Trends in wind energy costs (Source: U.S. DOE, 1998; <http://www.eren.doe.gov/wind/wttr.html>)



Wind technology does not have fuel requirements as do coal, gas, and petroleum generating technologies. However, both the equipment costs and the costs of accommodating special characteristics such as intermittence, resource variability, competing demands for land use, and transmission and distribution availability can add substantially to the costs of generating electricity from wind. For wind resources to be useful for electricity generation, the site must (1) have sufficiently powerful winds, (2) be located near existing transmission networks, and (3) be

economically competitive with respect to alternative energy sources. While the technical potential of wind energy to fulfill our need for energy services is substantial the economic potential of wind energy remains dependent on the cost of wind turbine systems as well as the economics of alternative options.

3.3. Potential for Wind Energy: Technical, Resource and Environmental Issues

The main technical parameter determining the economic success of a wind turbine system is its annual energy output, which in turn is determined by parameters such as average wind speed, statistical wind speed distribution, distribution of occurring wind directions, turbulence intensities, and roughness of the surrounding terrain. Of these the most important and sensitive parameter is the wind speed (where the power in the wind is proportional to the third power of the momentary wind speed), which increases with height above the ground. As a result vertical axis wind turbines have mostly been abandoned in favor of the taller traditional horizontal axis configuration. As accurate meteorological measurements and wind energy maps become more commonly available wind project developers are able to more reliably assess the long-term economic performance of wind farms.

Some of the problems with wind power involve siting wind turbines. In densely populated countries where the best sites on land are occupied there is increasing public resistance making it impossible to realize projects at acceptable cost. This is one of the main reasons that countries like Denmark and the Netherlands are concentrating on offshore projects, despite the fact that technically and economically they are expected to be less favorable than good land sites. On the other hand, in countries like the United Kingdom and Sweden offshore projects are being planned not due to scarcity of suitable land sites, but because preserving the landscape is such an important national value. Another obstacle can be that the best wind site locations are not in close proximity to populations with the greatest energy needs, as in the U.S. Midwest, making such sites impractical due to the high cost of transmission over long distances.

There has been a gradual growth of the unit size of commercial machines since the mid 70's. In the mid 70's the typical size of a wind turbine was 30 kW installed power. By 1998 the largest units installed had a capacity of 1.65 MW, and turbines with an installed power of 2 MW are now being introduced on the market, with 3 MW machines on the drawing board. The trend toward larger machines is driven by the demand side of the market to utilize economy of scale, reduce visual impact on the landscape per unit of installed power, and the expectation that the offshore potential will be developed soon. Recent technical advances have also made wind turbines more controllable and grid compatible and have reduced their number of components making them more reliable and robust.

Wind energy although considered an environmentally sound energy option does have several negative environmental aspects connected to its use. These include: acoustic noise emission, visual impact on the landscape, impact on bird's life, shadow caused by the rotor, and electromagnetic interference influencing the reception of radio, TV and radar signals. In practice the noise and visual impacts appear to cause the most problems for siting projects. Noise issues have been reduced by progress in aero-acoustic research providing design tools and blade configurations that have successfully made blades considerably quieter. The impact on bird's life

appears to be a relatively minor problem. For instance a research project in the Netherlands showed that birds casualties as a results of collisions with rotating rotor blades for a wind farm of 1000 MW is only a very small fraction of victims from hunting, high voltage lines and traffic estimating a maximum level of 6–7 bird collisions/turbine/year, (see Table 2). Avoiding endangered species habitats and major migration routes in the siting of wind farms can for the most part eliminate this problem.

Table 2. Comparison of estimates of annual total human-related bird-mortality in the Netherlands (Source: National Wind Coordinating Committee, Proceedings of National Avian-Wind Power Planning Meeting, 1994)

Causes of Death	# Bird Victims (100,000)
Road Kills	20 - 80
Power Lines	10 - 20
Hunting	6.5
Per 1,000 MW Wind Power	2.1 - 4.6

In addition to being cost-competitive and environmentally sound wind energy has several additional advantages over conventional fossil fuel power plants and even other renewable energy sources. First it is modular: that is, the generating capacity of wind farms can easily be expanded since new turbines can be quickly manufactured and installed, not true for either coal-fired or nuclear power plants. Furthermore, a repair to one wind turbine does not effect the power production of all the others. Second, the energy generated by wind turbines can pay for the materials used to make them in as short as 3 - 4 months for good wind sites. Thirdly, during normal operation they produce no emissions. One estimate of wind energy potential to reduce CO₂ emissions predicts that a 10 percent contribution of wind energy to the world’s electricity demand by 2025 would prevent the emission of 1.4 Gton/year of CO₂. Despite these advantages wind’s biggest drawback continues to be its intermittence and mismatch with power demand. Since large storage systems are not yet practical its use as a utility’s sole power source remains very limited with estimates for its practical integration into the power grid reaching only 10-20 percent of the total electricity supplied. Distributed wind facilities, as opposed to utility type windfarms, for which there is a growing interest, may help alleviate this problem.

Finally, there is also a strong and growing market for small wind turbines (under 100 kW) of which the U.S. is a leading manufacturer. Four very active U.S. manufacturers are estimated to cover a 30 percent market share worldwide. Small-scale turbines can especially play a significant role in rural and remote locations particularly in developing countries where access to the grid is either unlikely or extremely expensive.

3.4. Selected Country Profiles and Government Incentives to Promote Wind Energy

Incentives have long been viewed as a means of supporting technological developments until a new technology becomes cost-competitive. Wind-based electricity is not yet generally competitive with alternate sources of electricity such as fossil fuels. Thus, it is still dependent on non-market support for development to take place. Where sufficient support has been made

available, wind capacity has expanded. When support has been withdrawn, or is uncertain, wind energy development has substantially slowed.

The countries that have been fueling wind energy's growth throughout this decade have mainly been in the Northern Hemisphere, in particular Europe, where issues regarding the environment, fuel security and electricity-generating diversity are a priority. Of the 10 countries with the highest installed capacity at the end of 1999, only the United States, India and China lie outside Europe (Table 3).

Table 3. Installed wind power in 1997 and 1998 (Source: WEA, 2000)

	Installed MW 1997	Cumulative MW 1997	Installed MW 1998	Cumulative MW 1998
USA	29	1611	577	2141
Canada	4	26	57	83
Mexico	0	2	0	2
Latin America	10	42	24	66
Total Americas	43	1681	658	2292
Denmark	285	1116	310	1420
Finland	5	12	6	18
France	8	13	8	21
Germany	533	2081	793	2874
Greece	0	29	26	55
Ireland	42	53	11	64
Italy	33	103	94	197
Netherlands	44	329	50	379
Portugal	20	39	13	51
Spain	262	512	368	880
Sweden	19	122	54	176
United Kingdom	55	328	10	338
Other Europe	13	57	23	80
Total Europe	1318	4793	1766	6553
China	67	146	54	200
India	65	940	52	992
Other Asia	9	22	11	33
Total Asia	141	1108	117	1224
Australia & New Zealand	2	8	26	34
Pacific Islands	0	3	0	3
North Africa including Egypt	0	9	0	9
Middle East	8	18	0	18
Former Soviet Union	1	19	11	19
Total other continents and areas	11	57	37	83
Annual MW installed capacity	1513		2577	

worldwide				
Cumulative MW installed worldwide		7639		10153

Note: The cumulative installed capacity by the end of 1998 is not always equal to the 1997 data plus installed capacity during 1998, because of adjustments for decommissioned and dismantled capacity.

The stimulus for European growth continues to be regional and national policy incentives that have facilitated the birth and development of the wind energy industry. A combination of high energy prices, renewable energy subsidies that include investment and other fiscal incentives, and mandated purchases that include price support systems, are some of the most important parameters that have encouraged wind energy development in the European Union (EU). The heightened sensitivity that Europeans have for the environment has been a determining factor in setting such policies. Another important factor, although it is less frequently mentioned, is fuel security. Developing an indigenous resource helps diminish the dependence on imported energy sources, which is of strategic importance to many countries in the EU.

The wind energy boom in the last decade is being led by Germany, whose 7-year-old wind industry is now producing over 4000 MW, more than 1 percent of the nation's electricity. The U.S. is second in installed wind power worldwide at 2500 MW, about 0.2 percent of all U.S. grid-connected electricity generating capacity. Denmark, in third place with over 1700 MW, continues to be a world leader in the wind power industry and is already generating close to 10 percent of its electricity from wind. Fourth is Spain, which in the last couple of years has emerged as a major player in wind power, bypassing India, with an estimated 650 MW in new capacity installed in 1999, an 80 percent increase over the previous year, bringing their total to over 1400 MW.

3.4.1. United States

In the early 1980's, the United States accounted for 95 percent of the world's installed wind energy capacity. The U.S. share has since dropped to 22 percent in 1998. While other countries have increased their capacity the U.S. capacity has essentially stagnated, that is until last year when 732 MW in new capacity and 173 MW in replacement turbines were installed in a rush to beat an expiring production tax credit of 1.5 UScents/kWh for utility scale projects. Fortunately, this credit was extended through December 31, 2001.

The decline in the U.S. capacity share was due to a combination of economic factors and changes in government-sponsored support programs that impeded development of new capacity. The U.S. wind industry was born in 1981 in the aftermath of the world oil crises of 1973 - 1974 and 1978 - 1979. Wind energy was not cost-competitive with fossil-fuel energy, but Federal legislation guaranteed a market for wind-generated power and offered generous tax credits to developers of wind energy. Combined Federal and State investment tax credits could amount to 50 - 55 percent of investments in wind energy projects and were critical for establishing the wind industry. However, 1986 marked the beginning of the slowdown in U.S. wind energy development. The availability of relatively cheap oil and natural gas and improvements in gas generating technology, coupled with the expiration of Federal tax credits at the end of 1985, meant that

wind energy remained significantly more costly than fossil fuels. The tax credit incentives had been more effective in building capacity than in maintaining productivity, and wind energy generating technology failed to advance as initially anticipated. This trend appears to have reversed itself in the last two years with over a 30 percent increase in 1998 and 40 percent increase in 1999. This recent growth coupled with progressive state policies, the extension of the federal wind energy production tax credit, the recently announced “Wind Powering America” initiative for wind to power at least 5 percent of the nation’s electricity by 2020, and a maturing wind turbine technology appears to have signaled a rebirth for the industry in the U.S.

3.4.2. Germany

In contrast to the U.S., Germany has increased its wind energy production consistently and dramatically throughout the last decade. Germany overtook the United States in 1997 as the country with the highest installed wind capacity in the world. It’s mixture of government incentives including the Electric Feed-in Law, guaranteeing that renewable energy producers are paid up to 90 percent of the current domestic retail electricity price, and low interest loans in several regions, have helped make this the strongest wind market in the world. Germany recently passed a new law with the aim of doubling renewable energy’s share of electricity to 10 percent in the next decade. This took effect in April 2000, replacing the Electric Feed-in law, and it provides a fixed level of support for all green power.

3.4.3. Denmark

Denmark ranks as the world’s largest manufacturer and exporter of wind turbines manufacturing over 60 percent of the world’s turbines. They are five years ahead of their goal to produce 10 percent of their electricity from wind and their new goal is to supply 50 percent of electric generation from wind by 2030, in part through a 4000 MW offshore wind initiative. The Danish government has been a consistent, strong supporter of its wind industry and similar to Germany their Windmill Law required electric utilities to purchase output from private wind turbines at 85 percent of the consumer price of electricity plus giving an ecotax break of 9UScents/kWh. Due to policies encouraging ownership of equipment privately owned wind turbines represent 80 percent of the market. In addition, the electric utilities also received a 1.5 UScents/kWh production subsidy for wind power generation. Starting in 2000 the wind energy market is being transformed from a fixed-price system to a Renewable Portfolio Standard where by 2003 20 percent of the country’s electricity consumption will have to come from renewable sources; the current amount is between 12 to 14 percent. This will be achieved through the trading of “green certificates” issued to renewable energy generators in proportion to their energy production.

3.4.4. Spain

In Spain strong incentives for wind developers, coupled with regional incentives to spur local investment particularly in the manufacturing of equipment along with the willingness of banks to finance projects has created a wind program that barely existed 6 years ago. Like Germany and Denmark, Spain ensures a payment to wind producers equivalent to 80-90 percent of the retail rate. As a consequence, Spain’s wind energy growth holds the world record over the last two years. Although in the next few years the growth rate is expected to slow somewhat the wind

industry's strong political support and significant wind energy potential and available land suggests that rapid growth will continue for sometime into the future.

3.4.5. Great Britain

Another country worthy of note is Great Britain, which has been noticeably slower to develop its wind industry when compared to other countries in Europe. While some of the lowest cost, most competitive wind energy projects to date have come from the British Non-Fossil Fuel Obligation (NFFO) competitive bidding process few of the projects have actually resulted in increased wind generating capacity. This is at least due in part to wind farm energy projects awarded funding through NFFO having run into problems obtaining the permits to build in different regions, which have caused delays in their construction. The slowdown has worried the government, which will largely have to depend on wind energy to reach its commitments to lower greenhouse gas emissions. Parliament has set up a Planning Inspectorate to investigate those projects that have run into problems to try and resolve the pending issues that affect them. Much of the wind potential in the U.K. hinges on development of large-scale offshore wind farms, and it is still unclear how quickly the country will move toward constructing such projects. Most recently an offshore project to install two 2 MW turbines is expected to come on-line in August 2000. The future of wind in the U.K. remains uncertain

3.4.6. Developing Countries

Finally, among the developing countries India continues to be the leader followed by China. India had one of the fastest growing wind markets in the mid-90s but has since slowed substantially due to under performance of projects (often due to poor siting), transmission problems, and political and economic instability, all of which have affected investments in new projects. Extensive use of investment tax credits has also led to unsustainable revenue losses for the government. During the 1990s electricity consumption more than doubled in India, and despite huge expenditures in the power industry, the country still has a 12 percent electricity deficit and 20 percent peak power shortage. Due to these conditions, and the continued fast rate of growth in consumption, India continues to be considered a key market for wind developers. China remains mostly an untapped market with a huge future potential for wind energy. They have invested relatively little money into projects to date, which remain small and donor based. It is expected that major commercial development, possibly to take place in the next decade, will be needed for strong wind energy development to occur in China.

3.5. Conclusions

For the first time, we are seeing one of the emerging renewable energy generating options—wind power—in a position to compete with the generation technologies of the last century. A variety of players are engaged in pushing forward wind projects worldwide. Enron Wind Corporation acquired German turbine manufacturer Tacke; NEG Micon of Denmark has built manufacturing facilities in the U.S., Vestas of Denmark has built factories in Spain and India and many manufacturers have developed joint ventures in various countries around the world. This globalization trend is likely to continue as financial institutions are beginning to view the wind industry as a promising investment opportunity. As more countries are added to the wind energy

roster, uneven development focusing on a half-dozen key markets will most likely be replaced by more balanced growth. During the next couple of years, large-scale projects are expected to be developed in Egypt, Nicaragua, Costa Rica, Brazil, Turkey, Philippines, and several other countries, totaling thousands of MW of new installed capacity, and expanding the number of countries using their wind resources.

Yet, as land constraints, lower average wind speeds in future projects, as well as possibly lower energy prices impact the economics of future projects wind penetration will likely begin to saturate and the growth rates quoted above slow. This trend may be offset, however, by the use of larger, more efficient turbines, where the average size per turbine installed has already increased from 630 kW in 1997 to megawatt size systems in 1999, allowing operators to lower generation costs. The increase in capacity factor (annual energy output/output based on full time operation at rated power) from 20 percent to 25 percent also reflects improved efficiency and siting of projects. In addition, the future development of offshore wind farms will open up new frontiers in wind energy development.

The issue of wind power opportunity is likely to become increasingly relevant in determining its future use in world electricity supply. Understanding wind prospects is important in expected “normal” energy futures as well as for possible exceptional ones. As wind turbine costs decline and their performance improves, the extent to which wind resources, transmission and distribution networks, and market forces complement or offset these improvements becomes all the more pertinent for near and mid-term electricity supply. If these additional factors have little influence, then improved wind technologies may enjoy fairly rapid penetration into electricity markets. To the extent that economically accessible wind resources are soon exhausted, networks are full, or markets are resistant, however, wind power may find itself still a marginal source of electric power supply.

4. Solar Photovoltaic and Solar Thermal Technologies

There are two basic categories of technologies that convert sunlight into useful forms of energy, aside from biomass-based systems that do this in a broader sense by using photosynthesis from plants as an intermediate step. First, solar photovoltaic (PV) modules convert sunlight directly into electricity. Second, solar thermal power systems use focused solar radiation to produce steam, which is then used to turn a turbine producing electricity. The following provides a brief overview of these technologies, along with their current commercial status.

4.1. Solar Photovoltaics

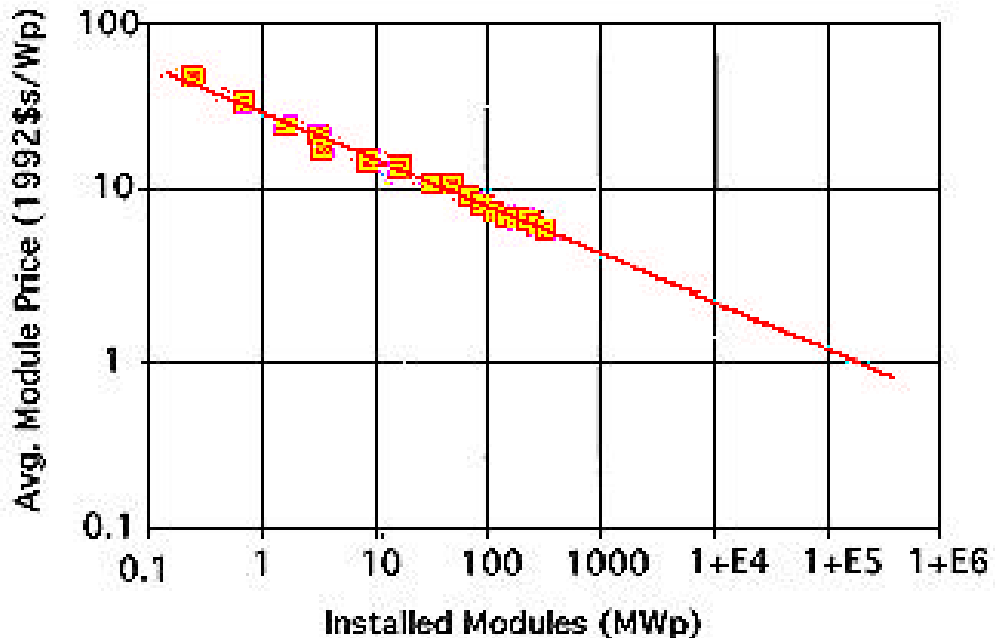
Solar PV modules are solid-state semiconductor devices with no moving parts that convert sunlight into direct-current electricity. The basic principle underlying the operation of PV modules dates back more than 150 years, but significant development really began following Bell Labs’ invention of the silicon solar cell in 1954. The first major application of PV technology was to power satellites in the late 1950s, and this was an application where simplicity and reliability were paramount and cost was a secondary concern. Since that time, enormous progress has been made in PV performance and cost reduction, driven at first by the U.S. space

program's needs and more recently through private/public sector collaborative efforts in the U.S., Europe, and Japan.

At present, annual global PV module production is over 150 MW, which translates into a more than \$1 billion/year business. In addition to the ongoing use of PV technologies in space, their present-day cost and performance also make them suitable for many grid-isolated and even grid-connected applications in both developed and developing parts of the world. PV technologies are potentially so useful that as their comparatively high initial cost is brought down another order of magnitude, it is very easy to imagine them becoming nearly ubiquitous late in the 21st century. PV systems would then likely be employed on many scales in vastly differing environments, from microscopic cells to 100 MW or larger 'central station' generating plants covering square kilometers on the earth's surface and in space. The technical and economic driving forces that favor the use of PV technologies in these widely diverse applications will be equally diverse. However, common among them will be the durability, high efficiency, quiet operation, and lack of moving parts that PV systems offer, and the fact that these attributes combine to provide a power source with minimum maintenance and unmatched reliability.

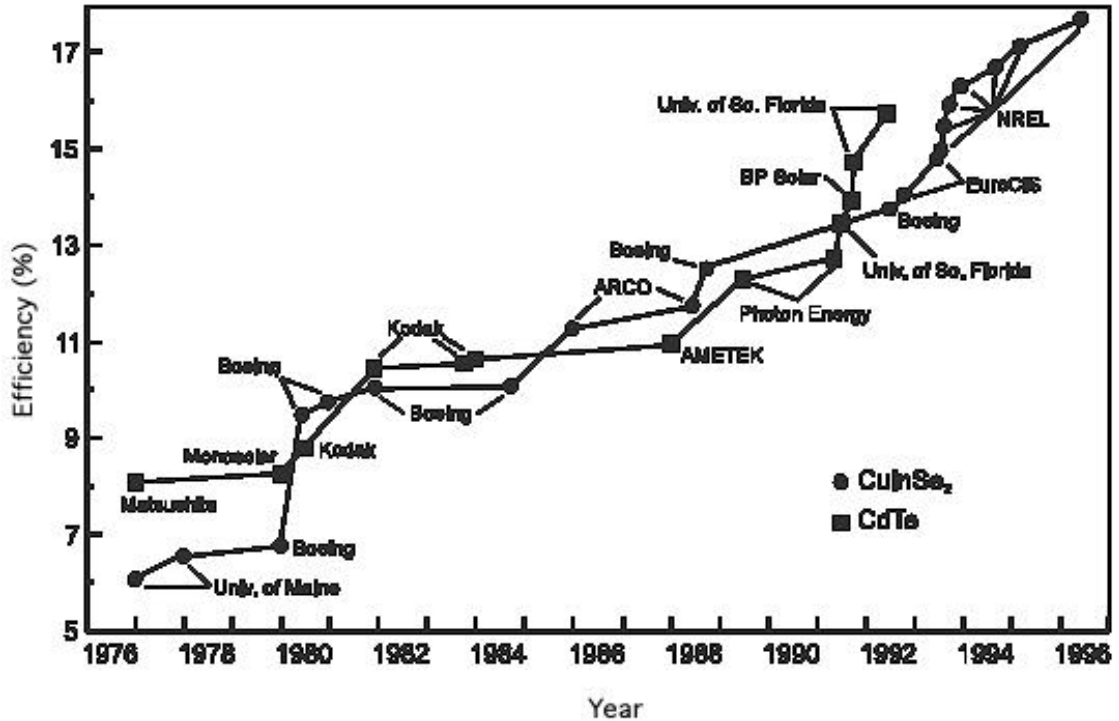
PV system cost and performance have been steadily improving in recent years. PV manufacturing costs have fallen from about \$30 per watt in 1976 to well under \$10 per watt by the mid-1990s as can be seen in Figure 5. Installed PV system costs today are about \$8.00 to \$12.00 per watt, depending on the level of solar insolation at the site and other factors. These installed system costs are expected by some analysts to reach a range of from \$3.00 to \$6.00 per watt by 2010, and if this is achieved PV systems could achieve a sales level of over 1,600 MW per year by that time.

Figure 5. PV module price trend from 1976 to 1994 along 82 percent progress ratio (Source: U.S. DOE, 1997)



PV efficiency has also increased markedly over the past few decades as shown in Figure 6.

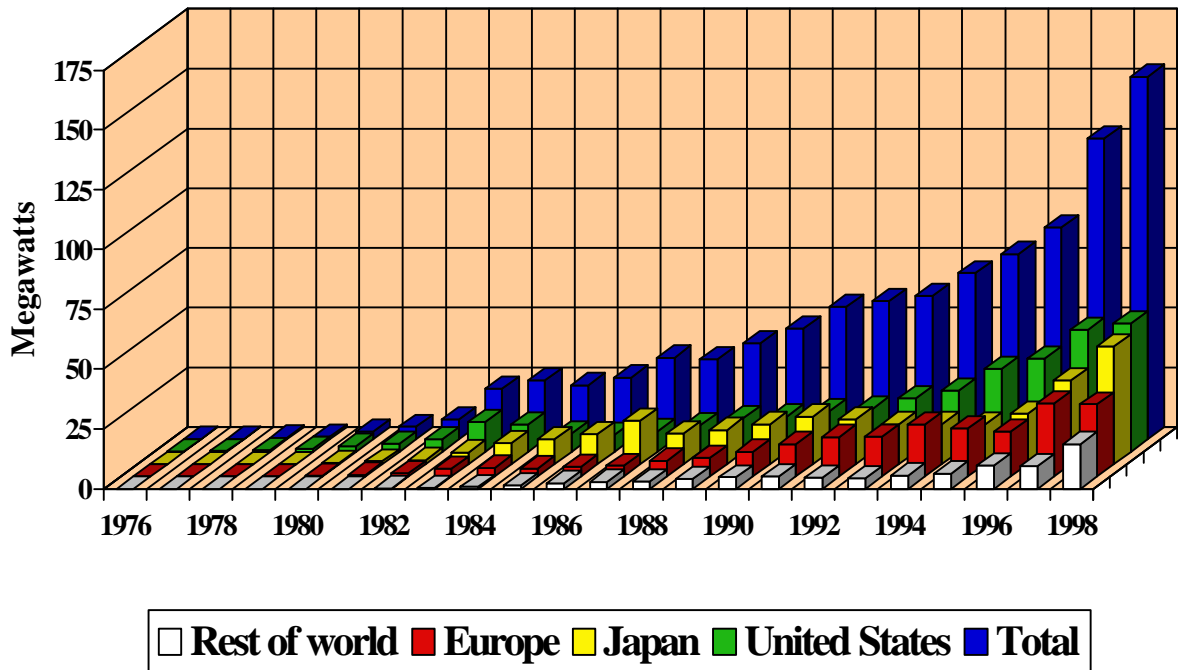
Figure 6. Progress in polycrystalline thin film laboratory cell efficiencies (Source: U.S. DOE, 1997)



The best thin film cells tested in laboratories in 1980 achieved an efficiency level of about 10 percent. This was improved to about 13 percent by 1990 and over 17 percent in recent years, for the best thin film cells made from copper indium diselenide (CuInSe₂) or cadmium telluride (CdTe). However, the modules that are currently being manufactured have somewhat lower efficiencies than these recent test cells, with typical values in the range of 9-11 percent for CuInSe₂ and CdTe modules, and 8-10 percent for the more common amorphous silicon modules. The efficiency gains made over the last decade or so at the cell level will slowly translate into higher efficiency manufactured products, and this should combine with cell and module manufacturing cost reductions to aid in producing the reductions in per-watt installed system costs discussed above.

Figure 7, below, shows PV shipments by region and for the entire world, from 1976 to 1998. As shown in the figure, PV sales are growing rapidly. In fact, the sales growth rate throughout the 1990s was approximately 30 percent per year.

Figure 7. Regional and global photovoltaic shipments to different regions worldwide, 1976-1998 (Source: PV News, P. Maycock, editor; yearly February editions)



Thus, PV systems are declining in cost, improving in efficiency, and increasing rapidly in sales. The cost of electricity produced from PV systems is still higher than from most other competing technologies, at about 30 cents per kWh, but these costs are expected to continue to decline steadily. In fact, the U.S. Department of Energy projects that the cost of generating electricity from utility-scale PV systems could be below 10 UScents/kWh by 2010, while by 2020 this cost could fall to about 6 UScents/kWh. Meanwhile, costs of electricity from residential PV systems could reach about 18 UScents/kWh by 2010, and 10 UScents/kWh by 2020. These potential reductions in cost, combined with the simplicity, versatility, reliability, and low environmental impact of PV systems, should help them to become increasingly important sources of economical premium-quality power over the next 20 to 30 years.

4.2. Solar Thermal Systems

Solar thermal power systems use various techniques to focus sunlight to heat an intermediary fluid, known as heat transfer fluid that then is used to generate steam. The steam is then used in a conventional steam turbine to generate electricity. At present, there are three solar thermal power systems currently being developed: parabolic troughs, power towers, and dish/engine systems. Because these technologies involve a thermal intermediary, they can be readily hybridized with fossil fuels and in some cases adapted to utilize thermal storage. The primary advantage of hybridization and thermal storage is that the technologies can provide dispatchable power and operate during periods when solar energy is not available. Hybridization and thermal storage can enhance the economic value of the electricity produced, and reduce its average cost.

Parabolic trough solar thermal systems are commercially available. These systems use parabolic trough-shaped mirrors to focus sunlight on thermally efficient receiver tubes that contain a heat transfer fluid. This fluid is heated to about 390° C. (734° F) and pumped through a series of heat exchangers to produce superheated steam that powers a conventional turbine generator to produce electricity. Nine of these parabolic trough systems, built in 1980s, are currently generating 354 MW in Southern California. These systems, sized between 14 and 80 MW, are hybridized with up to 25 percent natural gas in order to provide dispatchable power when solar energy is not available.

Power tower solar thermal systems are in the demonstration and scale-up phase. They use a circular array of heliostats (large individually-tracking mirrors) to focus sunlight onto a central receiver mounted on top of a tower. The first power tower, Solar One, was built in Southern California and operated in the mid-1980s. This initial plant used a water/steam system to generate 10 MW of power. In 1992, a consortium of U.S. utilities joined together to retrofit Solar One to demonstrate a molten-salt receiver and thermal storage system. The addition of this thermal storage capability makes power towers unique among solar technologies by allowing dispatchable power to be provided at load factors of up to 65 percent. In this system, molten-salt is pumped from a “cold” tank at 288° C. (550° F) and then cycled through the receiver where it is heated to 565° C. (1,049° F) and finally returned to a “hot” tank. The hot salt can then be used to generate electricity when needed. Current designs allow storage ranging from 3 to 13 hours.

Dish/engine solar thermal systems, currently in the prototype phase, use an array of parabolic dish-shaped mirrors to focus solar energy onto a receiver located at the focal point of the dish. Fluid in the receiver is heated to 750° C (1,382° F) and used to generate electricity in a small engine attached to the receiver. Engines currently under consideration include Stirling and Brayton-cycle engines. Several prototype dish/engine systems, ranging in size from 7 to 25 kW, have been deployed in various locations in the U.S. and elsewhere. High optical efficiency and low startup losses make dish/engine systems the most efficient of all solar technologies, with electrical conversion efficiencies of up to 29.4 percent. In addition, the modular design of dish/engine systems make them a good match for both remote power needs, in the kilowatt range, as well as grid-connected utility applications in the megawatt range.

System capital costs for these systems are presently about \$4-5 per watt for parabolic trough and power tower systems, and about \$12-13 per watt for dish/engine systems. However, future cost projections for trough technology are higher than those for power towers and dish/engine systems due in large part to their lower solar concentration and hence lower operating temperature and efficiency. By 2030, the U.S. Department of Energy forecasts costs of \$2.70 per watt, \$2.50 per watt, and \$1.30 per watt, respectively, for parabolic trough, power tower, and dish engine systems.

5. Hydropower

5.1. Introduction

Hydropower is the largest renewable resource used for electricity. It plays an essential role in many regions of the world with more than 150 countries generating hydroelectric power. A

survey in 1997 by The International Journal on Hydropower & Dams found that hydro supplies at least 50 percent of national electricity production in 63 countries and at least 90 percent in 23 countries. About 10 countries obtain essentially all their commercial electricity from hydro, including Norway, several African nations, Bhutan and Paraguay.

There is about 700 GW of hydro capacity in operation worldwide, generating 2600 TWh/year (about 19 percent of the world's electricity production). About half of this capacity and generation is in Europe and North America with Europe the largest at 32 percent of total hydro use and North America at 23 percent of the total. However, this proportion is declining as Asia and Latin America commission large amounts of new hydro capacity.

Small, mini and micro hydro plants (usually defined as plants less than 10 MW, 2 MW and 100kW, respectively) also play a key role in many countries for rural electrification. An estimated 300 million people in China, for example, depend on small hydro.

5.2. Capacity and Potential

There is vast unexploited potential worldwide for new hydro plants, particularly in the developing countries of Asia, Latin America and Africa while most of the best sites have already been developed in Europe and North America. There is also upgrading potential at existing schemes though any future hydro projects will, in general, have to satisfy stricter requirements both environmentally and economically than they have in the past.

As shown in Table 4 the world's gross theoretical hydropower potential is about 40000 TWh/year, of which about 14000 TWh/year is technically feasible for development and about 7000 TWh/year is currently economically feasible. The last figure fluctuates most being influenced not only by hydro technology, but also by the changing competitiveness of other energy/electricity options, the status of various laws, costs of imported energy/electricity, etc.

Table 4. Hydroelectric theoretical, technically feasible, and economically feasible potential as well as installed and under construction capacity in 1997 by region (Source: WEA, 2000)

Region	Gross Theoretical Potential	Technically Feasible Potential	Economically Feasible Potential	Installed Hydro Capacity	Hydro Power Production	Hydro Capacity Under Construction
	TWh/year	TWh/year	TWh/year	GW	TWh/year	GW
North America	5817	1509	912	141.2	697	0.9
Latin America and Caribbean	7533	2868	1199	114.1	519	18.3
Western Europe	3294	1822	809	16.3	48	2.5
Central and Eastern Europe	195	216	128	9.1	27	7.7

Former Soviet Union	3258	1235	770	146.6	498	6.7
Middle East and North Africa	304	171	128	21.3	66	1.2
Sub-Saharan Africa	3583	1992	1288	65.7	225	16.6
Centrally Planned Asia	6511	2159	1302	64.3	226	51.7
South Asia*	3635	948	103	28.5	105	13.0
Pacific Asia*	5520	814	142	13.5	41	4.7
Pacific OECD	1134	211	184	34.2	129	0.8
World Total	40784	13945	6965	654.8	2581	124.1

** Several South Asian and other Pacific Asian countries do not release their economically feasible potential resulting in numbers that are too low.*

As can be seen in Table 4 the biggest growth in hydro generation is expected in the developing countries where there is still a large potential for hydro development, while relatively little growth is expected in most OECD countries where more than 65 percent of the economic potential is already in use. Thus, at least in the near future, hydro will likely remain the main source of electricity generation in developing countries that possess adequate water resources.

Until recent years there has been less than 100 GW (about 350 TWh/year) of new hydro capacity under construction at any one time, equivalent to less than 15 percent of the capacity in operation. The figure has now risen, reflecting China's vast construction program, which includes the 18.2 GW Three Gorges Project, now in its second phase of construction. Most new hydro capacity is under construction in Asia and South America. China has by far the most, with about 50 GW under way. Brazil has largest resources in world (800,000 GWh/year) of economically exploitable capacity and Norway depends almost entirely hydro for its electricity needs.

Hydropower continues to be the most efficient way to generate electricity. Modern hydro turbines can convert as much as 90 percent of the available energy into electricity. The best fossil fuel plants are only about 50 percent efficient. In the U.S., hydropower is produced for an

average of 0.7 cents/kWh. This is about one-third the cost of using fossil fuel or nuclear and one-sixth the cost of using natural gas. Hydro resources are also widely distributed compared with fossil and nuclear fuels and can help provide energy independence for countries without fossil fuel resources.

There is also significant, widespread activity in developing small, mini and micro hydro plants. At least forty countries, particularly in Asia and Europe, have plants under construction and even more have plants planned. China, Brazil, Canada, Turkey, Italy, Japan and Spain all have plans for more than 100 MW of new capacity.

5.3. Small Hydro

Small-scale hydro is mainly ‘run of river,’ so does not involve the construction of large dams and reservoirs. It also has the capacity to make a more immediate impact on the replacement of fossil fuels since, unlike other sources of renewable energy, it can generally produce some electricity on demand (at least at times of the year when an adequate flow of water is available) with no need for storage or backup systems. It is also in many cases cost competitive with fossil-fuel power stations, or for remote rural areas, diesel generated power.

Small hydro has a large, and as yet untapped, potential in many parts of the world. It depends largely on already proven and developed technology with scope for further development and optimization. Least-cost hydro is generally high-head hydro since the higher the head, the less the flow of water required for a given power level, and so smaller and less costly equipment is needed. While this makes mountainous regions very attractive sites they also tend to be in areas of low population density and thus low electricity demand and long transmission distances often nullify the low cost advantage. Low-head hydro on the other hand is relatively common, and also tends to be found in or near concentrations of population where there is a demand for electricity. Unfortunately, the economics also tend to be less attractive unless there are policy incentives in place to encourage their development.

5.4. Environmental and Social Impacts

Although hydroelectricity is generally considered a clean energy source, it is not totally devoid of greenhouse gas emissions (GHG) and it can often have significant adverse socio-economic impacts. There are arguments now that large-scale dams actually do not reduce overall GHG emissions when compared to fossil fuel power plant. To build a dam significant amounts of land need to be flooded often in densely inhabited rural area, involving large displacements of usually poor, indigenous peoples. Mitigating such social impacts represents a significant cost to the project, which if it is even taken into consideration, often not done in the past, can make the project economically and socially unviable.

Environmental concerns are also quite significant, as past experience has shown. This includes reduction in biodiversity and fish populations, sedimentation that can greatly reduce dam efficiency and destroy the river habitat, poor water quality, and the spread of water-related diseases. In fact, in the U.S. several large power production dams are being decommissioned due to their negative environmental impacts. Properly addressing these issues would result in an

enormous escalation of the overall costs for producing hydropower making it far less competitive than is usually stated. As many countries move toward an open electricity market this fact will come into play when decisions regarding investments in new energy sources are being made. If the large hydro industry is to survive it needs to come to grips with its poor record of both cost estimation and project implementation.

5.5. Conclusions

Hydropower is a significant source of electricity worldwide and will likely continue to grow especially in the developing countries. While large dams have become much riskier investment there still remains much unexploited potential for small hydro projects around the world. It is expected that growth of hydroelectricity will continue but at a slower rate than that of the 70's and 80's. Thus, the fraction of hydroelectricity in the portfolio of primary sources of energy, which is today at 19 percent, is expected to decrease in the future. Improvements and efficiency measures are needed in dam structures, turbines, generators, substations, transmission lines, and environmental mitigation technology if hydropower's role as a clean renewable energy source is to continue to be supported.

6. Geothermal Energy

6.1. Introduction

Geothermal energy, the natural heat within the earth, arises from the ancient heat remaining in the Earth's core, from friction where continental plates slide beneath each other, and from the decay of radioactive elements that occur naturally in small amounts in all rocks. For thousands of years, people have benefited from hot springs and steam vents, using them for bathing, cooking, and heating. During this century, technological advances have made it possible and economic to locate and drill into hydrothermal reservoirs, pipe the steam or hot water to the surface, and use the heat directly (for space heating, aquaculture, and industrial processes) or to convert the heat into electricity.

The amount of geothermal energy is enormous. Scientists estimate that just 1 percent of the heat contained in just the uppermost 10 kilometers of the earth's crust is equivalent to 500 times the energy contained in all of the earth's oil and gas resources. Yet, despite the fact that this heat is present in practically inexhaustible quantities, it is unevenly distributed, seldom concentrated and often at depths too great to be exploited industrially and economically.

Geothermal energy has been produced commercially for 70 years for both electricity generation and direct use. Its use has increased rapidly during the last three decades and from 1975 – 1995 the growth rate for electricity generation worldwide has been about 9 percent per year and for direct use of geothermal energy it has been about 6 percent per year. In 1997 geothermal resources had been identified in over 80 countries and there were quantified records of geothermal utilization in at least 46 countries.

6.2. Capacity and Potential

Exploitable geothermal systems occur in a number of environments. High temperature fields used for conventional power production occur mainly in areas of high geological activity. Low temperature resources for direct heating can be found in most countries and can now also be accessed using recently developed ground source heat pumps.

The worldwide use of geothermal energy amounts to about 44 TWh/year of electricity and 38 TWh/year for direct use as shown in Table 5. While geothermal accounts for only about 0.3 percent of the total electrical power generated worldwide, amongst renewable sources (excluding hydro) it ranks first at around 80 percent of the total. It is currently estimated that the geothermal potential of the world for electricity production is 12,000 TWh/year and for direct use it is estimated to be even larger at 600,000 EJ. A very small fraction of the geothermal potential has therefore been developed so far, and an accelerated use of geothermal energy in the near future is certainly feasible. In addition, the technology for both electricity generation and direct application is mature and accessible. Thus, the question of its future development depends upon whether it is economically competitive with other energy sources in the different markets around the world. Currently, the electric generation cost is variable, but averages around 4 UScents/kWh, while direct utilization production costs, though highly variable, are commonly under 2UScents/kWh.

Table 5. Electricity generation and direct use of geothermal energy in 1997 (Source: WEA, 2000)

Region	Electricity Generation			Direct Use		
	Installed Capacity MW _e	Total production		Installed capacity MW _t	Total production	
		GWh/year	%		GWh/year	%
European Union	754	3832		1031	3719	
Other Europe	112	471		4089	16 058	
Total Europe	866	4303	10	5120	19 777	52
N. America	2849	16 249		1908	3984	
Latin America	959					
Total Americas	3808	6869	53	1908	3984	10
		23 118				
Asia	2937	13 045	30	3075	12 225	32
Oceania	365	2901	6	264	1837	5
Africa	45	390	1	71	355	1
World Total	8021	43 756	100	10 438	38 178	100

Table 6 shows the installed geothermal electricity generation capacity in 1990, 1995, and 1998 for a selection of countries. The growth of the total generation capacity from 1990-1995 was about 16 percent and in 1995-1998 about 17 percent. The largest additions in generation capacity during 1990-1998 have been in the Philippines (957 MW_e), Indonesia (445 MW_e), Italy (224

MW_e), Japan (315 MW_e), Costa Rica (120 MW_e), Iceland (95 MW_e), USA (75 MW_e), New Zealand (62 MW_e), and Mexico (43 MW_e). The most progressive of these countries, the Philippines, plans to add some 580 MW_e to their installed capacity during 1999-2008.

Table 6. Installed geothermal electricity generation capacity (MW_e) by country and year (Source: International Geothermal Association, 1998; <http://www.demon.co.uk/geosci/igahome.html>)

Country	1990	1995	1998
Argentina	0.7	0.7	0
Australia	0	0.2	0.4
China	19	29	32
Costa Rica	0	55	120
El Salvador	95	105	105
France (Guadeloupe)	4	4	4
Guatemala	0	0	5
Iceland	45	50	140
Indonesia	145	310	590
Italy	545	632	769
Japan	215	414	530
Kenya	45	45	45
Mexico	700	753	743
New Zealand	283	286	345
Nicaragua	70	70	70
Philippines	891	1191	1848
Portugal (Azores)	3	5	11
Russia	11	11	11
Thailand	0.3	0.3	0.3
Turkey	20	20	20
USA	2775	2817	2850
Totals	5867	6798	8239

In the industrialized countries where installed electrical capacity is already very high, geothermal energy is unlikely in the near-term future to account for more than 1 percent of the total. On the other hand, in developing countries, with still relatively limited electrical consumption, but with good geothermal prospects, electrical generation from geothermal energy could make a significant contribution to the total installed electrical capacity. For example, today already 22 percent of the electricity in the Philippines comes from geothermal sources, 17 percent in Nicaragua, 12 percent in El Salvador, 11 percent in Costa Rica and 6 percent in Kenya.

Direct application of geothermal energy can involve a wide variety of end uses using mostly existing technology. The technology, reliability, economics, and environmental acceptability of direct use of geothermal energy have been demonstrated throughout the world.

In comparison with electricity production from geothermal energy direct utilization has several advantages. It has higher energy efficiency, 50 - 70 percent as opposed to 5 - 20 percent for conventional geothermal electric plants, generally a much shorter development time, and normally less capital investment is needed. In addition, direct application can use both high- and low-temperature geothermal resources and is therefore much more widely available in the world. Direct application is, however, much more site specific for the market, as steam and hot water is rarely transported long distances from the geothermal site. The longest geothermal hot water pipeline in the world is 63 km, in Iceland. The various types of direct use of geothermal energy include space heating, the dominant type (33 %) of direct use in the world, bathing/swimming/balneology (19 %), greenhouses (14 %), heat pumps (12 %) for air cooling and heating, fish farming (11 %), and industry (10 %).

Table 7 shows the installed capacity and produced energy in the top ten direct use countries in the world. It is worth noting that the two countries with the highest energy production, Japan and Iceland, are not the same as the two with the highest installed capacities, China and USA. The reason for this is the variety in the load factors for the different types of use.

Table 7. Top ten countries in geothermal energy production for direct use (Source: WEA, 2000)

Country	Installed Capacity (GW_t)	Heat Production (TW_h/year)
Japan	1.16	7.50
Iceland	1.44	5.88
China	1.91	4.72
USA	1.91	3.97
Hungary	0.75	3.29
Turkey	0.64	2.50
New Zealand	0.26	1.84
France	0.31	1.36
Italy	0.31	1.03

Germany	0.31	0.81
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6.3. Environmental Impacts

Geothermal fluids contain variable concentrations of gases, largely nitrogen and carbon dioxide with some hydrogen sulphide and smaller proportions of ammonia, mercury, radon and boron. Most of these chemicals are concentrated in the disposal water which is usually reinjected back into the drill holes so that there is minimal release into the environment. The concentrations of the gases are usually low enough not to be harmful or else the abatement of toxic gases can be managed with current technology.

Carbon dioxide is the major component of the noncondensable gases in the steam, but its emission into the atmosphere per kWh is well below the figures for natural gas, oil, or coal-fired power plants. Hydrogen sulphide is the pollutant of most major concern in geothermal plants yet even the sulfur emitted with no controls is only half what is emitted from a coal-fired plant. Overall, with present technology able to control the environmental impact of geothermal energy development, it is considered to be a relatively benign source of energy.

6.4. Conclusions

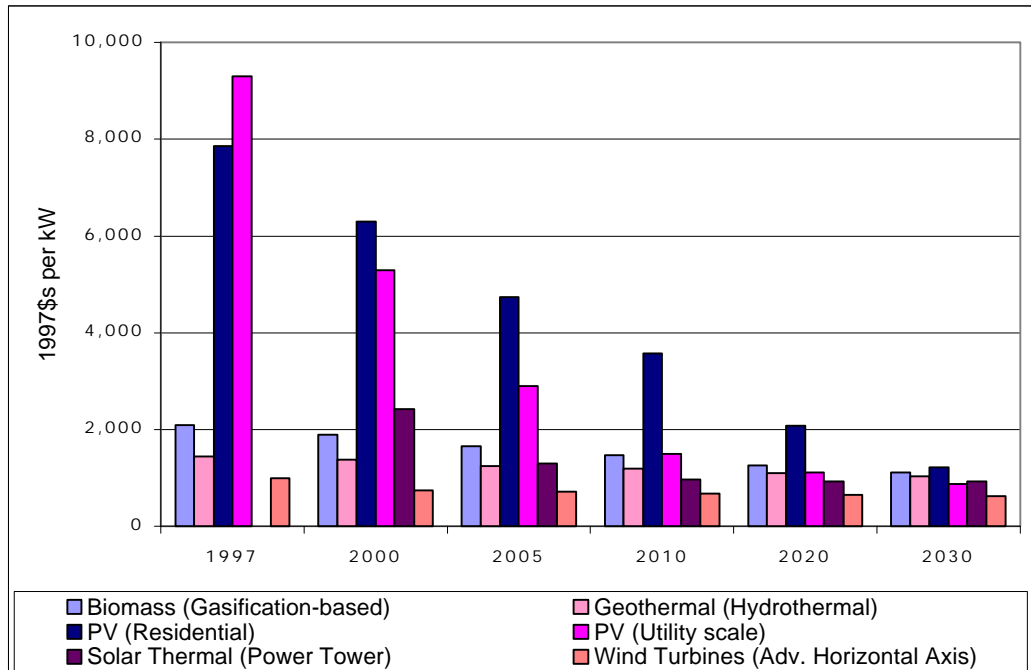
Geothermal as noted is not available everywhere especially with the resources required for the production of electrical energy on an industrial scale. Nonetheless, geothermal energy is generally cost competitive with conventional energy sources and is produced by well proven conventional technology. It is reliable and has been used for the more than half of the last century to heat large municipal districts, as well as to feed power plants generating hundreds of megawatts of electricity. It has strong potential to continue to expand, especially in the developing countries and is a clean energy source which can help contribute to reducing our greenhouse gas emissions. It is felt that in the near-term the future development of geothermal could help fulfill a bridging function during the next few decades as other more modern clean fuel technologies and renewables mature enough to provide a meaningful share of the world energy supply.

7. Renewable Energy System Cost and Performance

7.1. Recent progress in Renewable Energy System Cost and Performance

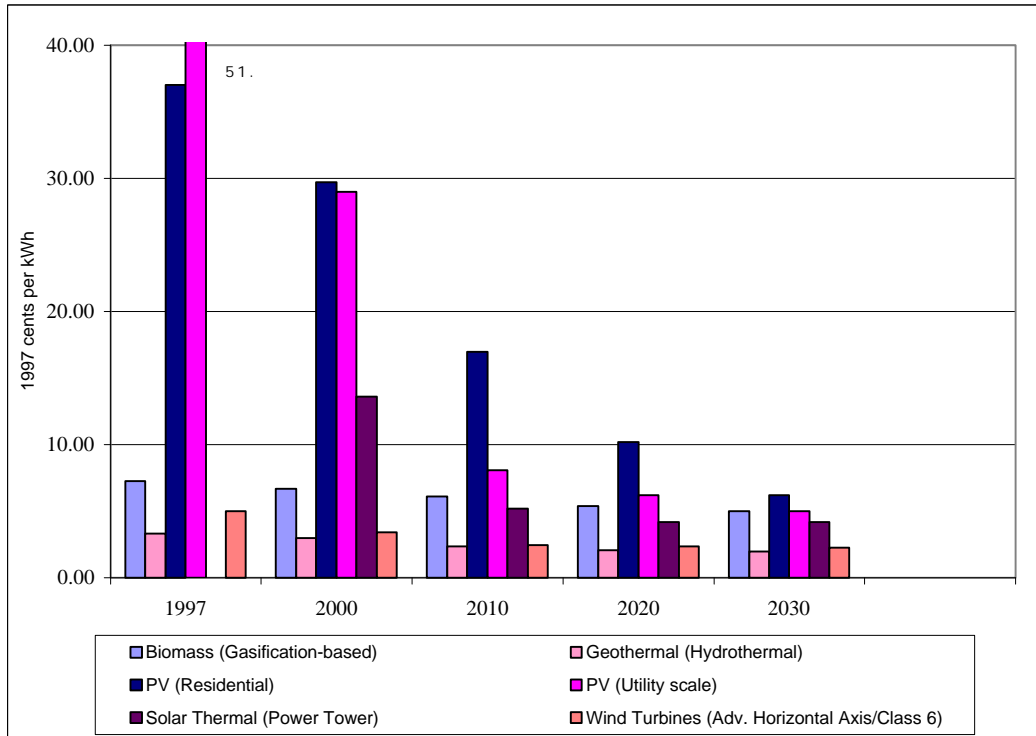
As previously described there has been significant progress in cost reduction made by wind and PV systems, while biomass, geothermal, and solar thermal technologies are also experiencing cost reductions, and these are forecast to continue. Figure 8 presents forecasts made by the U.S. DOE for the capital costs of these technologies, from 1997 to 2030.

Figure 8. Capital cost forecasts for renewable energy technologies (Source: U.S. DOE, 1997)



Of course, capital costs are only one component of the total cost of generating electricity, which also includes fuel costs, and operation and maintenance costs. In general, renewable energy systems are characterized by low or no fuel costs, although operation and maintenance (O&M) costs can be considerable. It is important to note, however, that O&M costs for all new technologies are generally high, and can fall rapidly with increasing familiarity and operational experience. Renewable energy systems such as photovoltaics contain far fewer mechanically active parts than comparable fossil fuel combustion systems, and therefore are likely in the long-term to be less costly to maintain. Figure 9 presents U.S. DOE projections for the levelized costs of electricity production from these same renewable energy technologies, from 1997 to 2030.

Figure 9. Levelized cost of electricity forecast for renewable energy technologies (Source: U.S. DOE, 1997)

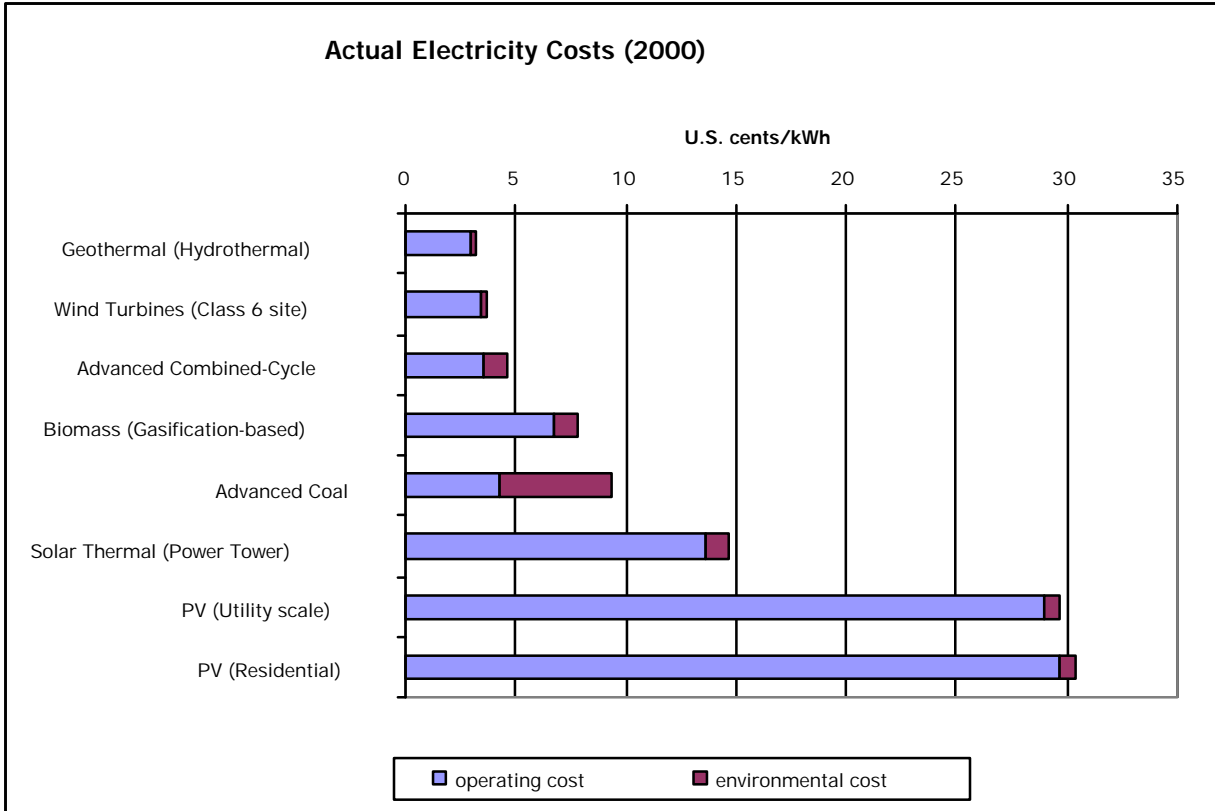


Given these likely capital and levelized system cost reductions, recent analyses have shown that additional generating capacity from wind and solar energy can be added at low incremental costs relative to additions of fossil fuel-based generation. These incremental costs would be further offset by environmental and human health benefits. Furthermore, a U. S. National Renewable Energy Laboratory (NREL) analysis shows that geothermal and wind energy could actually become more economic than coal in the next 15 years.

Another analysis conducted by the Renewable Energy Policy Project (REPP) shows that adding 3,050 MW of wind energy production in Texas, over a ten-year period, would entail only modest additional costs to residential customers. REPP estimates these additional costs to be about 75 cents per month for a household using 1,000 kWh per month, or about \$9 annually.

The economic case for renewables looks even better when environmental costs are considered along with capital and operating costs. As shown in Figure 10, geothermal and wind can be competitive with modern combined-cycle power plants, and geothermal, wind, and biomass all have lower total costs than advanced coal-fired plants, once approximate environmental costs are also included.

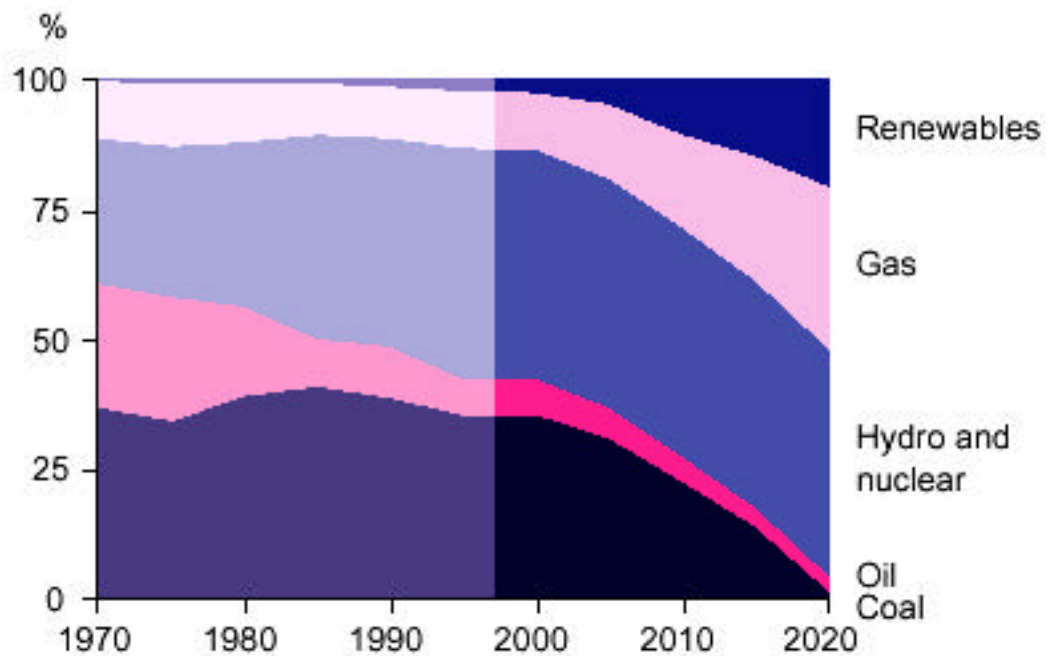
Figure 10. Actual electricity costs 2000 (Sources: U.S. DOE, 1997; U.S. DOE, 2000)



Shell Petroleum has made one of the highest profile projections of future renewables growth. As shown in Figure 11, Shell projects that renewables could constitute about 15 percent of the OECD's energy production by 2020, and that renewables and natural gas combined could account for about 50 percent of total production.

Figure 11. OECD electricity mix (Source: Shell Petroleum, 2000)

OECD Electricity Mix



As noted above, the remarkable difference between the setting for renewable energy today, relative to the past 30 years, is that renewable and other clean energy technologies are actually now becoming economically competitive, and the push to develop them is no longer being driven solely by environmental concerns. With regard to prospects for investing in companies developing clean energy resources, Merrill Lynch's Robin Batchelor recently stated:

“This is not an ethical investment opportunity, it's a straightforward business opportunity.”

Mr. Batchelor also noted that the traditional energy sector has lacked appeal to investors in recent years because of heavy regulation, low growth, and a tendency to be highly cyclical. He has identified 300 companies worldwide whose aim is to develop wind, solar, and wave power technologies and to advance capabilities in energy storage, conservation, and on-site power generation.

Further evidence of the impending transition to renewable energy systems can be found in recent corporate re-organization among the world's largest oil companies. Corporate giants such as Shell and BP/Amoco, which would now like to be known as “energy companies” rather than “oil companies,” have recently re-organized into a broader array of business units, including those exclusively focused on renewables. Such subsidiary units now include “Shell Renewables,” and “BP Solar.”

7.2. Lessons Learned in Developing Countries

In developing nations, renewable energy technologies are increasingly used to address energy shortages and to expand the range of services in both rural and urban areas. In Kenya over 80,000 small (20 - 100 Wp) solar PV systems have been commercially financed and installed in homes, battery charging stations, and other small enterprises. Meanwhile, a government program in Mexico has disseminated over 40,000 such systems. In the Inner Mongolian autonomous region of China over 130,000 portable windmills provide electricity to about one-third of the non-grid-connected households in this region.

These case studies demonstrate that the combination of sound national and international policies and genuinely competitive markets – the so-called ‘level playing field’ -- can be used to generate sustainable markets for clean energy systems. They also demonstrate that renewable energy systems can penetrate markets in the developing world, even where resources are scarce, and that growth in the renewables sector need not be limited to applications in the developed world. Just as some developing countries are bypassing construction of telephone wires by leaping directly to cellular-based systems, so too might they avoid building large, centralized power plants and instead develop decentralized systems. In addition, to help mitigating the environmental costs of electrification, this strategy can also reduce the need for the construction of large power grids.

Despite their limited recent success, renewable energy sources have historically had a difficult time breaking into markets that have been dominated by traditional, large-scale, fossil fuel-based systems. This is partly because renewable and other new energy technologies are only now being mass produced, and have previously had high capital costs relative to more conventional systems, but also because coal, oil, and gas-powered systems have benefited from a range of subtle subsidies over the years. These include military expenditures to protect oil exploration and production interests overseas, the costs of railway construction that have enabled economical delivery of coal to power plants, and a wide range of smaller subsidies.

However, another limitation has been the intermittent nature of some renewable energy sources, such as wind and solar. One solution to this last problem is to develop diversified systems that maximize the contribution of renewable energy sources but that also uses clean natural gas and/or biomass-based power generation to provide base-load power when the sun is not shining and the wind is not blowing. Using a range of different renewable energy technologies to provide energy for a region can also help to mitigate the intermittent nature that some of them exhibit. Even when there is no wind blowing there may be strong solar insolation, and *vice versa*.

In essence, however, renewable energy technologies face a similar situation confronting any new technology that attempts to dislodge an entrenched technology. For many years, we have been “locked-in” to a suite of fossil fuel and nuclear-based technologies, and many of our secondary systems and networks have been designed and constructed to accommodate these. Just as electric-drive vehicles face an uphill battle to dislodge gasoline-fueled, internal combustion engine vehicles, so too do solar, wind, and biomass technologies face a difficult time upstaging modern coal, oil, and natural gas power plants. This “technological lock-in” situation has several important implications. First, various types of feedstock and fuel delivery infrastructure have been developed over the years to support conventional energy sources, and in some cases these would require modifications to support renewable energy technologies. This would entail additional cost, tipping the table away from the new challengers. Second, the characteristics of

conventional energy systems have come to define how we believe these systems should perform, and new renewable energy technologies that offer performance differences compared to conventional technologies (such as intermittent operation) may raise doubts among potential system purchasers. Third, to the extent that new technologies are adopted, early adoptions will lead to improvements and cost reductions in the technologies that will benefit later users, but there is no market mechanism for early adopters to be compensated for their experimentation that later provides benefits to others. Since there is no compensatory mechanism, few are likely to be willing to gamble on producing and purchasing new technologies, and the market is likely to under-supply experimentation as a result.

Hence, particularly in the absence of policy intervention (discussed below), we may remain locked-in to existing technologies, even if the benefits of technology switching overwhelm the costs. There are numerous examples, however, of an entrenched or locked-in technology being first challenged and ultimately replaced by a competing technology. This process is generally enabled by a new wave of technology, and it is sometimes achieved through a process of hybridization of the old and the new. Technological "leapfrogging" is another possibility, but this seems to occur relatively rarely. A prime example of the hybridization concept is in the case of the competition between gas and steam powered generators, which dates back to the beginning of the century. From about 1910 to 1980, the success of steam turbines led to a case of technological lock-in, and to the virtual abandonment of gas turbine research and development. However, partly with the aid of "spillover" effects from the use of gas turbines in aviation, the gas turbine was able to escape the lock-in to steam turbine technology. First, gas turbines were used as auxiliary devices to improve steam turbine performance, and then they slowly became the main component of a hybridized, "combined-cycle" system. In recent years, orders for thermal power stations based primarily on gas turbines have increased to more than 50 percent of the world market, up from just 15-18 percent in 1985.

Furthermore, increasing returns to adoption, or "positive feedbacks," can be critical to determining the outcomes of technological competitions in situations where increasing returns occur. These increasing returns can take various forms, including the following: industrial learning (e.g., learning-by-doing in manufacturing, along with economies of scale, leads to production cost declines); network related externalities (e.g., networks of complementary products, once developed, encourage future users); returns on information (e.g. information about product quality and reliability decreases uncertainty and reduces risk to future adopters); and/or better compatibility with other technologically interdependent systems. Where increasing returns are important, as in most technology markets, the success with which a challenger technology can capture these effects and enter the virtuous cycle of positive feedbacks may, in conjunction with chance historical events, determine whether or not the technology is ultimately successful.

Thus, just as the hybridization between gas and steam turbines gave gas turbines a new foothold in the market, so might hybridization between gas and biomass-fueled power plants allow biomass to eventually become a more prominent energy source. Hybridization of intermittent solar and wind power with other clean "baseload" systems could help to allow solar and wind technologies to proliferate, and perhaps with advances in energy storage systems they could ultimately become dominant. Once they are able to enter the market, through whatever means, these technologies can reap the benefits of the virtuous cycle brought on by increasing returns to

adoption, and clearly this is already beginning to happen with several new types of renewable energy technologies.

7.3. Leveling the Playing Field

As shown in Figure 7.3, above, renewable energy technologies tend to be characterized by relatively low environmental costs. In an ideal world, this would aid them in competing with conventional technologies, but of course many of these environmental costs are “externalities” that are not priced in the market. Only in certain areas and for certain pollutants do these environmental costs enter the picture, and clearly further internalizing these costs would benefit the spread of renewables. The international effort to limit the growth of greenhouse emissions through the Kyoto Protocol may lead to some form of carbon-based tax, and this could prove to be an enormous boon to renewable energy industries. However, support for the Kyoto Protocol among industrialized countries remains relatively weak, particularly in the U.S., and any proposed carbon-based taxation scheme will surely face stiff opposition.

Perhaps more likely, concern about particulate matter emission and formation from fossil-fuel power plants will lead to expensive mitigation efforts, and this would help to tip the balance toward cleaner renewable systems. In a relatively controversial move, the U.S. Environmental Protection Agency (EPA) has recently proposed new ozone and particulate matter (PM) standards that are even more stringent than the current standards that remain unattained in some U.S. urban areas. The EPA has justified these new regulations with analysis that shows that new standards are necessary to provide increased protection against a wide range of potential health impacts. For example, the EPA estimates that even if Los Angeles County were to meet the existing PM standards, 400 to 1,000 deaths per year would still occur as a result of exposure to very fine PM (under 2.5 microns in diameter) that presently is not regulated. The combination of increased pressure to attain ozone and PM standards will further complicate siting of new fossil-fueled power plants in some areas of the U.S., particularly where they are now required to find “offsets” for their pollution impacts. This will indirectly but surely benefit renewable energy technologies, which do not typically face these difficulties in obtaining siting permits.

7.3.1. Public and Private Sector Investment Issues

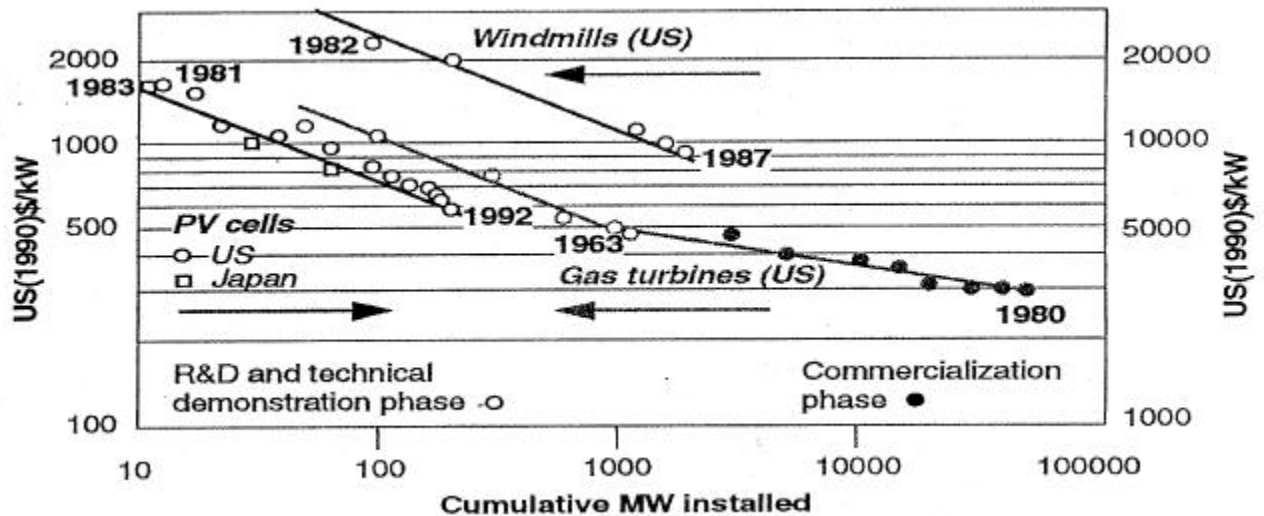
A fundamental problem with any new technology is that by definition it does not have the track-record of performance that exists for older, more established systems. Proponents of existing technologies in mistaken arguments against technological change often cite this fact. New technologies and operational procedures do present greater risks, but at the same time greater opportunities for innovation and profit. Emerging energy systems were long seen as an area of risky investments, with the history of renewable energy systems seen as the primary illustration of that ‘fact’. It has been argued that this pattern is not only illusory, but is largely a self-fulfilling prophecy. Larger gains, both to individual companies and to society, typically stem from carefully targeted but consistently pursued avenues of research, innovation, and implementation. Renewable energy systems offer this same combination of increased uncertainty, great promise, and the potential for significant innovations and profits.

There are two principal rationales for government support of research and development (R&D) to develop clean energy technologies (CET). First, conventional energy prices generally do not reflect the social cost of pollution. This provides a rationale based on a well-accepted economic argument, for subsidizing R&D for CETs as potential alternatives to polluting fossil fuels. Second, private firms are generally unable to appropriate all the benefits of their R&D investments. Consequently, the social rate of return for R&D exceeds available private returns, and firms therefore do not invest enough in R&D to maximize social welfare. Thus, innovation “spillover” among CET firms is a form of positive externality that justifies public R&D investment.

The conventional wisdom is that government should restrict its support to R&D and let the private sector commercialize new technologies. Failed CET commercialization subsidies (e.g. the U.S. corn ethanol and synfuels programs) bolster this view. Nonetheless, there are compelling arguments for public funding of Market Transformation Programs (MTPs) that subsidize demand for some CETs in order to help commercialize them. Further, the argument that it may not be worthwhile for firms to invest in new technologies because of the spillover effects is generally false as well. Early investment in new technologies in promising market sectors has proven to be the best strategy for firms interested in long-term and not simply short-term profitability.

A principal motivation for considering MTPs is inherent in the production process itself. When a new technology is first introduced it is invariably more expensive than established substitutes. There is, however, a clear tendency for the unit cost of manufactured goods to fall as a function of cumulative production experience. Cost reductions are typically very rapid at first, but taper off as the industry matures. This relationship is called an ‘experience curve’ when it accounts for all production costs, and it can be described by a progress ratio (PR) where unit costs fall by $100 \times (1 - PR)$ percent with every doubling of cumulative production. Typical PR values range from 0.7 to 0.9 and are widely applicable to technologies such as toasters, microwave ovens, solar panels, windmills and essentially any good that can be manufactured in quantity. For example, Figure 12 presents PRs for photovoltaics, windmills, and gas turbines. All three have initial PRs of approximately 0.8, which is a typical value observed for many products. After 1963 the gas turbine PR increased substantially, however indicating an attenuation of experience effects.

Figure 12. Progress ratios for photovoltaics, windmills, and gas turbines (Source: IIASA/WEC, 1995)



The benefits of production experience may accrue primarily to the producing firm, or they may spillover to its competitors. Among other channels, experience spillovers could result from hiring competitors' employees, reverse engineering rivals' products, informal contacts among employees of rival firms, or even industrial espionage. If firms retain the benefits of their own production experience they have an incentive to consider experience effects when deciding how much to produce. Consequently, they will "forward-price," producing at a loss initially to bring down their costs and thereby maximize profit over the entire production period. It has been shown that, in each period, firms maximize profit by setting marginal revenue equal to their true marginal cost (TMC). For a firm with a discount rate of zero, TMC is defined as the cost of the last unit the firm plans to produce. If the firm has a positive discount rate its TMC will be somewhat higher. However, due to experience effects the TMC is always lower than current marginal cost (except for the very last unit produced).

In addition, unless there is 100 percent spillover, the first-best social optimum requires regulating a single firm such that it produces in every period up to the level where price equals true marginal cost. This policy would require subsidizing the monopolist since it would be selling units for less than their current marginal cost in every period except the last. Absent regulation, when experience spillover is low, cumulative production experience gives incumbent firms widening cost advantages over potential entrants. Thus early entrants can cut back their output and raise prices above the competitive level without prompting other firms to enter. The incentive to forward price partially mitigates the problem, but output remains below the social optimum.

When experience does spill over substantially, firms still do not produce enough to maximize social efficiency. This follows because experience becomes a positive externality analogous to the R&D appropriability problem. Thus, firms insufficiently forward-price because they do not value the portion of their experience benefits that accrue to other firms.

To summarize, regardless of the level of spillover, strong experience effects imply that output is less than the socially efficient level. That is, some consumers would be willing to pay more than the cost of additional production, but the market fails to facilitate these mutually beneficial trades. MTPs can improve social welfare by correcting the output shortfall associated with these experience effects.

Moreover, as with R&D, MTPs also help to promote the use of CETs as alternatives to polluting fossil fuel technologies, and thereby reduce the social costs of pollution. When politically possible, the first-best policy is to fully internalize pollution costs (*e.g.* through pollution taxes set at the marginal social cost of the pollution externality or tradable emissions permits set at the socially optimal pollution level). Governments chronically fail to achieve this, however, providing another clear rationale to support MTPs.

When evaluating MTPs, it is essential to account for positive feedback between the demand response and experience effects. An MTP increases the quantity produced in the first year and, due to experience effects, year 2 unit costs are lower than they would have been without the additional production from the MTP. These lower costs, in turn, imply that the quantity demanded in year 2 is higher. This “indirect demand effect,” in turn, adds to cumulative production experience and further lowers unit costs in future years. This process continues indefinitely, though it gradually dissipates once the MTP is discontinued. Accounting for these indirect demand effects substantially raises the benefit-cost ratio (BCR) of typical MTPs. Even without accounting for environmental benefits, the case studies of MTPs targeting photovoltaics and efficient lighting show positive BCRs of 1.05 and 1.54, respectively.

These results suggest a role for MTPs in national and international technology policies; however, the costs of poor program design, inefficient implementation, or simply choosing the “wrong” technologies can easily outweigh cost reduction benefits. This suggests that MTPs be limited to emergent CETs with a steep industry experience curve, a high probability of major long-term market penetration once subsidies are removed, and a price elasticity of demand of approximately unity or greater. The condition that they be clean technologies mitigates the risk of poor MTP performance by adding the value of displaced environmental externalities. The other conditions ensure a strong indirect demand effect. Finally, as with energy R&D policy, public agencies should invest in a portfolio of new CETs in order to reduce overall MTP program performance risk through diversification.

8. Conclusions

In conclusion, we believe that the promise of renewable energy has now become a reality. Both solar photovoltaics and wind energy are experiencing rapid sales growth, declining capital costs and costs of electricity generated, and continued performance increases. Because of these developments, market opportunity exists now to both innovate and to take advantage of emerging markets, with the additional assistance of governmental and popular sentiment. The development and use of these sources can enhance diversity in energy supply markets, contribute to securing long term sustainable energy supplies, make a contribution to the reduction of local and global atmospheric emissions, provide commercially attractive options to meet specific

needs for energy services particularly in developing countries and rural areas, and create new employment opportunities.

While fossil fuels will remain in the fuel mix for the foreseeable future, current high petroleum costs, transient or not, illustrate the degree of social and political ill-will (e.g. European gas shortages and protests) that energy insecurity can generate. Integration of renewable energy supplies and technologies into the mix can help to temper the cyclical nature of fossil fuel markets, and can give renewables a foothold from which they can continue to grow and compete. There are many opportunities for creative integration of renewables into energy production systems. These include combined fossil and biomass-fueled turbines and combinations of intermittent renewable systems and base-load conventional systems with complementary capacity profiles. Strategies such as these, in conjunction with development of off-grid renewable systems in remote areas, are likely to provide continued sales growth for renewable and other CETs for many years to come.

At present, however, the rates and levels of investment in innovation for renewable and other CETs are too low. This is the case because of market imperfection that undervalues the social costs of energy production, the fact that firms cannot typically appropriate the full value of their R&D investments in innovation, and because new technologies are always characterized by uncertain performance and thus greater risk compared to their more well-developed rivals. These issues suggest a role for public sector involvement in developing markets for renewable energy technologies through various forms of market transformation programs.

Finally, we conclude that current energy producers are in the best position to capture new renewable energy markets. These producers have the capital needed to make forays into these markets, and the most to lose if they do not invest and renewable energy technologies continue to flourish. We believe that artful introduction and integration of renewable energy technologies into energy production systems, along with encouragement from the public sector where appropriate, can provide a path that eventually leads to heavy reliance on renewable energy systems in the future. This future would be more environmentally and socially sustainable than one we would achieve by following a more “conservative” path based on continued reliance on fossil fuels. This latter path in many ways implies higher risks to human and ecological health and welfare over time, and it is a path that is increasingly difficult to justify based on the performance that renewables are now achieving.

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the key global trends for 1999, includes charts, tables and analysis of topics ranging from nuclear power generating capacity to the proliferation of genetically modified crops.]

Author Biographies

Antonia V. Herzog

Post-doctoral Fellow
Energy and Resources Group
Renewable and Appropriate Energy Laboratory
University of California, Berkeley
Email: aherzog@socrates.berkeley.edu

B.A. Physics, Vassar College, 1987

B. E. Engineering, Dartmouth College, Thayer School of Engineering, 1988

M.S. Applied Physics, Columbia University, School of Engineering and Applied Science, 1989

Ph.D. Physics, University of California, San Diego, 1996

Antonia V. Herzog received her Ph.D. in physics from the University of California, San Diego in 1996 for research on the low-temperature quantum mechanical behavior of one- and two-dimensional superconducting, metallic, and insulating nano-wires. She was then awarded a Sloan Post-doctoral Fellowship in Neurobiology by the Salk Institute for Biological Studies in La Jolla, California where she worked in the Systems Neurobiology Laboratory for a year studying the functional connectivity of cortical neurons in the visual cortex using intracellular electrophysiological recordings in brain tissue. Becoming increasingly interested in the interface between science and public policy she made a break from basic research and moved to Washington, DC where she initially worked at the American Association for the Advancement of Science (AAAS) as a consultant exploring various issues related to the ethical, legal and social implications of science and technology before being awarded the 1998-1999 American Physical Society Congressional Science Fellowship. As a Congressional Science Fellow Dr. Herzog spent a year working in Senator John D. Rockefeller IV's (Democrat-West Virginia) personal office as a Legislative Assistant covering science and technology and energy and environmental issues. Her work included legislation to promote alternative fuel vehicles, increase non-defense research and development funding, and facilitate technology transfer from the federal labs to the private sector. A growing concern with sustainable and environmentally sound international development and aid particularly in the energy sector prompted Dr. Herzog to join Dr. Daniel Kammen's Renewable and Appropriate Energy Laboratory (RAEL) in the Energy and Resources Group at the University of California, Berkeley beginning in January of 2000. She has received the prestigious University of California President's Postdoctoral Fellowship for a renewable energy power generation development project based in Zimbabwe, Africa. Generally her interests include the dissemination of renewable and appropriate energy systems in the developing countries, the potential socioeconomic and environmental impacts of renewable energy technologies and resource management systems locally and globally, and the impacts of climate change policy in the developing countries particularly the potential of the Clean Development Mechanism to foster sustainable development.

Timothy E. Lipman

Post-doctoral Fellow

Energy and Resources Group
Renewable and Appropriate Energy Laboratory
University of California, Berkeley
Email: telipman@socrates.berkeley.edu

B.A. Anthropology, Stanford University, 1990
M.S. Transportation Technology and Policy, University of California, Davis, 1998
Ph.D. Environmental Policy Analysis, University of California, Davis, 1999

Timothy E. Lipman completed a Ph.D. degree in Environmental Policy Analysis with the Graduate Group in Ecology at the University of California at Davis in December 1999. He then served as Associate Director of the Fuel Cell Vehicle Center at the Institute of Transportation Studies at UC Davis, and is now a Post-doctoral Fellow with the Energy and Resources Group at the University of California at Berkeley. In March 1998, Dr. Lipman received an M.S. degree in the technology track of the new UC Davis Graduate Group in Transportation Technology and Policy. While enrolled at UC Davis, Dr. Lipman worked as a researcher ITS-Davis on a CALSTART neighborhood electric vehicle project and on a California Air Resources Board electric vehicle cost and performance study, as well as participating in various smaller projects. He has authored or co-authored several journal articles and ITS-Davis research reports on policies to encourage the production and use of neighborhood electric vehicles, on the potential use of hydrogen as a transportation fuel, on the manufacturing costs of electric vehicle technologies, and on greenhouse gas emissions from transportation fuel cycles. He has authored papers for annual meetings of the Transportation Research Board, the Electric Vehicle Symposium, and the National Association of Environmental Professionals. Dr. Lipman has received several fellowships and awards, including the 1999 Council of University Transportation Centers "Charlie Wootan" dissertation award, a 1998 IGERT teaching fellowship, a 1997 University of California Transportation Center Dissertation Grant, a 1996 ENO Foundation Fellowship, a 1995 University of California Transportation Center Dissertation Grant, and a 1994 Chevron Foundation Fellowship. Dr. Lipman is also a graduate of Stanford University, where in 1990 he completed a self-designed B.A. in Anthropology, focusing on environmental and technology transfer issues in the developing world. He has previously worked as an environmental analyst and technical writer under a Boeing Aerospace, Inc. contract with the NASA-Ames Research Center in Mountain View, California, and as a policy intern at the Bank Information Center in Washington, D.C.

Daniel M. Kammen

Associate Professor of Energy and Society
Energy and Resources Group
Director, Renewable and Appropriate Energy Laboratory
University of California, Berkeley
Email: dkammen@socrates.berkeley.edu

B.A. Physics, Cornell University, 1984
M.A. Physics, Harvard University, 1986
Ph.D. Physics, Harvard University, 1988

Daniel M. Kammen received his doctorate in physics for work on theoretical solid state physics and computational biophysics. He was then the Wezmamm & Bantrell Postdoctoral Fellow at the California Institute of Technology in the Divisions of Engineering, Biology, and the Humanities (1988 - 1991). At Caltech and then as a Lecturer in Physics and in the Kennedy School of Government at Harvard University, Kammen developed a number of projects focused on renewable energy technologies and environmental resource management. At Harvard he also worked on risk analysis as applied to global warming and methodological studies of forecasting and hazard assessment. Kammen received the 1993 21st Century Earth Award, recognizing contributions to rural development and environmental conservation from the Global Industrial and Policy Research Institute and *Nihon Keizai Shimbun* in Japan. From 1993 - 1998 Kammen was an Assistant Professor of Public and International Affairs in the Woodrow Wilson School of Public and International Affairs at Princeton University. Kammen played a key role in developing the interdisciplinary Science, Technology, and Environmental Policy (STEP) Program at Princeton, which awards undergraduate and masters certificates and a doctoral degree. He has been Chair of STEP for the past four years and co-chair before that. In July of 1998 Kammen joined the interdisciplinary Energy and Resources Group (ERG) at the Berkeley as an Associate Professor of Energy and Society. Kammen is also the founding director of a new Renewable and Appropriate Energy Laboratory (RAEL) that is based in Department of Nuclear Engineering at Berkeley. He has been a Visiting Lecturer at the University of Nairobi, and is a Permanent Fellow of the African Academy of Sciences where he directs a field research and training program on energy and sustainable development in Africa. His research interests include: the science, engineering, management, and dissemination of renewable energy systems; health and environmental impacts of energy generation and use; rural resource management, including issues of gender and ethnicity; international R&D policy, climate change; and energy forecasting and risk analysis. He is the author of over 110 journal publications, several edited volumes, a book on environmental, technological, and health risks (*Should We Risk It?*, Princeton University Press, 1989) and numerous reports on renewable energy and development. He has been featured on radio, network and public broadcasting television and in print as an analyst of energy, environmental, and risk policy issues and current events. Kammen advises the U. S. and Swedish Agencies for International Development, the World Bank, and the Presidents Committee on Science and Technology (PCAST). Further information on his research, publications, teaching and policy work is available at: URL: <http://socrates.berkeley.edu/~dkammen>.

