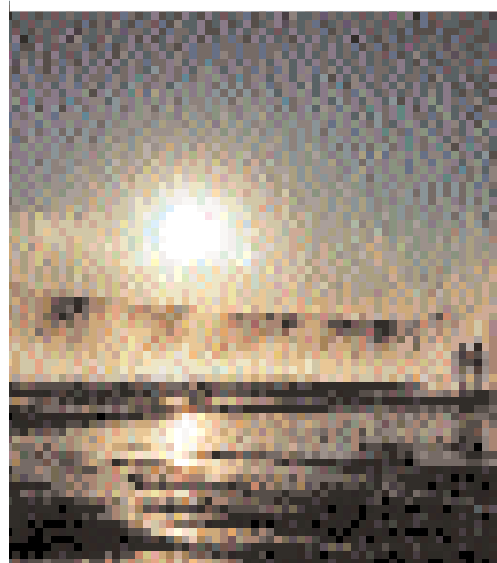
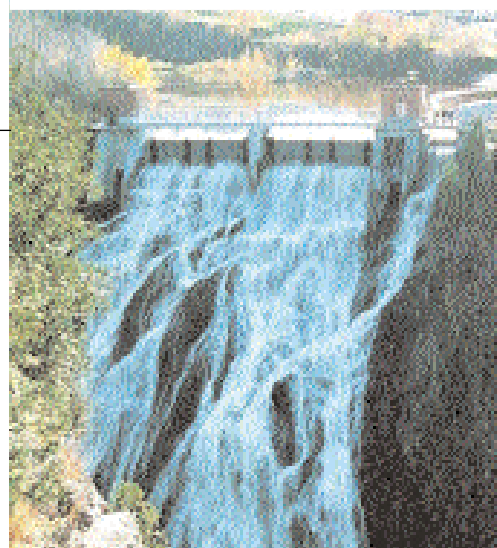
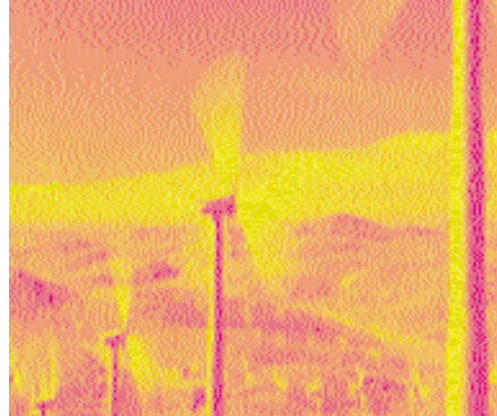


Natural Selection

Evolving Choices

for Renewable Energy

Technology and Policy





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Before you read this booklet . . .

. . . consider that the 21st century presents the nations of the world with a simple, yet profound truth: the future is a matter of human *choice*. Embedded in this truth is the fact that every choice we make today will have consequences well into the future.

We therefore need to make wise technology choices, not only for ourselves, but for generations yet to come. Energy lies at the heart of the world's economic development. Sound energy choices are therefore fundamental if we want to achieve sustainable development. The task will be not be easy, as history is littered with examples of well-intentioned decisions resulting in serious and unforeseen consequences.



Klaus Töpfer, Executive Director, UNEP

The discovery of a large hole in the ozone layer over Antarctica in 1975, for example, stunned the world's scientist and engineers. When chlorofluorocarbons (CFCs) began to be used widely in the 1960s as propellants in aerosol cans and in refrigeration, no one believed the non-toxic, non-flammable "wonder gases" were also highly efficient ozone destroyers, and could cause serious environmental harm. When computer programmers in the 1980s deliberately used two digits to represent a specific year instead of four to save money, they had no idea that the resulting Year 2000 bug (Y2K) would end up costing the world's governments and companies an estimated \$500 billion¹ to eliminate. Similarly, we now understand that the use of fossil fuels has serious environmental consequences. Fossil fuels provide three-quarters of the energy needed to drive a \$35 trillion world economy—a situation that is rapidly degrading the earth's natural systems. Slowly, we are realising that without healthy natural *ecologies*, we will not have healthy human *economies*.

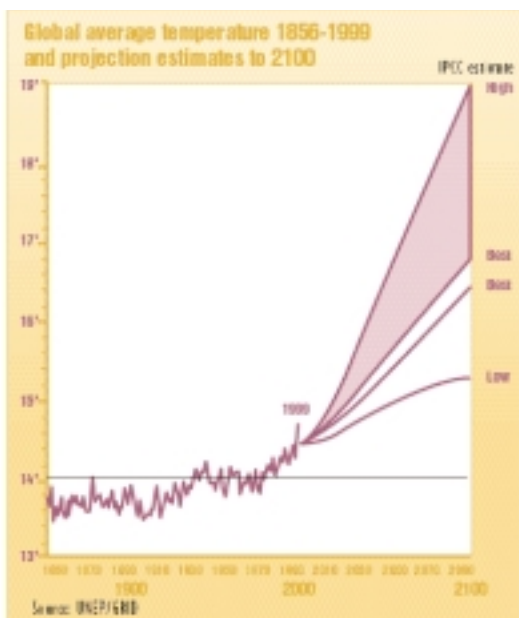
Our natural ecologies, however, are in a state of crisis. According to the United Nations Environment Programme (UNEP) GEO 2000 report, the time for a rational, well-planned transition to sustainable systems is quickly disappearing. Full-scale emergencies now exist in the use of water and land resources, forest destruction has gone too far to prevent irreversible damage in many areas, and urban air pollution is reaching crisis dimensions in many of the megacities of the developing world. The use of energy—or the demand for energy—is intimately tied to all of these emergencies.

For example, much of the air pollution that kills an estimated 500,000 people each year comes from burning fossil fuels in power stations, industrial furnaces, and motor vehicles, which produces small particles that can be

deeply inhaled into the lungs. Air pollution also causes an estimated four to five million new cases of chronic bronchitis, as well as millions of cases of other serious illnesses.² The economic burden of this pollution is estimated at 0.5 to 2.5 percent of world GNP, some \$150–750 billion per year.

These facts alone are reason enough to find new sources of energy and change the way it is used. However, the world's increasing appetite for fossil fuels is creating an even more compelling reason to accelerate the switch to clean forms of energy, namely global climate change.

Climate scientists almost unanimously agree that the accumulation of carbon dioxide and other heat-trapping greenhouse gases, mainly from the combustion of fossil fuels, will change the earth's climate. Scientists cannot yet make specific predictions about how the climate will change on a *regional* or *local* level, but they do agree that there is enough certainty of adverse climate change on a *global* level to recommend serious cuts in the emission of six main greenhouse gases.³





(Photo: Topham Picturepoint)

According to the best available science, sometime near the middle of this century the concentration of carbon dioxide in the atmosphere will double from that of the pre-industrial era to a level not seen for 400,000 years. As a result of this doubling, scientists estimate that some elements of global climate change are now inevitable. This is cause enough for concern, but scientists also fear that if the complex atmospheric system is “pushed” too quickly, and carbon dioxide levels *triple*, the results may be catastrophic. Nations with low-lying land exposed to the ocean are particularly at risk, as a warming earth would result in the thermal expansion of water and melting polar ice over land areas,⁴ causing ocean levels to rise.

Within this context, the nations of the world face an unprecedented challenge: ensuring that economic development continues and expands, while at the same time dramatically reducing the environmental impact of that development. This challenge, however, also presents an unparalleled opportunity to create new economies and societies. In the next two decades alone, an estimated \$9–15 trillion will be invested in new power sector projects. If a majority of this investment is directed towards clean energy technologies, the nations of the world will enjoy a global economy that is more secure, more robust, and much cleaner than that of the 20th century.

This is particularly relevant to developing countries, who now have an excellent opportunity to bypass the polluting energy path of developed countries. As the information in this booklet demonstrates, a sustainable energy path using renewable energy technology can create not only clean energy, but environmental security and regional development as well. Decision-makers who believe the use of large power stations is the best energy solution will be surprised to learn that the average size for a new power generation unit in the United States has declined by a factor of ten in less than two decades.

There are no technical, financial, or economic reasons why the nations of the world cannot enjoy the benefits of both a high level of energy service and a better environment. Clearly the combined effects of environmental damage and depleted non-renewable resources will ultimately shift human economies to sustainable energy systems. How soon that shift occurs, however, ultimately depends on what actions are taken now.

Natural Selection: Evolving Choices for Renewable Energy Technology and Policy has been designed to help you, the policy or decision-maker, create that shift sooner. In Part 1, you will find a brief, but thorough, overview of major renewable energy technologies followed, in Part 2, by a discussion of the policy frameworks that will further their deployment. This is intended to create a firm foundation of knowledge on which you can base action. Following Part 2, there is a brief discussion of scenarios that can lead us to a sustainable energy future.

Please read the booklet carefully, and share its content with colleagues. Use the information to ensure that the next energy decision you make is both well-informed and another step on the path to sustainable development.

Klaus Töpfer
Executive Director
United Nations Environment Programme

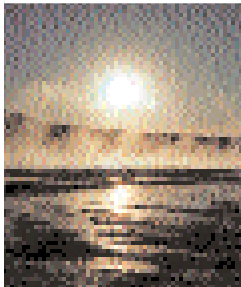
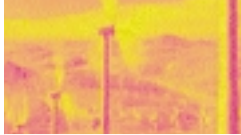


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"There is nothing so powerful as an idea whose time has come"

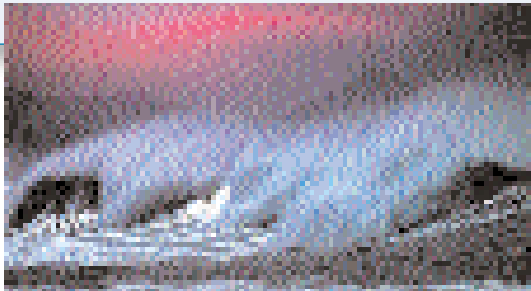
— Albert Einstein

Renewable energy is abundant, clean, and inexhaustible. It is also the most cost-effective energy source for a variety of applications, meeting between 15 and 20 percent of total world energy demand and 24 percent of the world's total electricity supply.⁵ Renewable energy in the form of traditional biomass fuels, such as wood and crop residues, represents about 14 percent of the world's total energy consumption—a larger share than coal (12 percent).

Defining Renewable Energy

Sources of renewable energy exist in the form of direct and indirect solar radiation, the heat of the earth (geothermal energy), and the gravitational effects of the moon that creates the tides. Direct solar radiation striking the earth also drives the global weather system and photosynthesis. This, in turn, creates the wind and waves, as well as biomass (plant and animal matter). The energy in falling water may also be considered a renewable energy source but only if the local environmental impacts are sustainable. Generally, new large-scale hydropower schemes are not considered a source of renewable energy due to their substantial environmental impacts.

Renewable energy can be converted to many other energy forms. Electricity can be generated from solar, wind, biomass, geothermal, hydropower, and ocean resources. Heat can be generated from solar thermal and geothermal sources, while biofuels such as ethanol and methane can be obtained from combinations of renewable sources.



(Photo: Topham Picturepoint/UNEP \ Schinogrotzki)

However, the contribution of newer renewable energy technologies (RETs) is increasing rapidly, in spite of new competition from deregulated energy markets. From a small base in the 1970s, biomass, geothermal, solar, small-scale hydropower, and wind technologies have grown proportionally faster than any other electricity supply technology, and now supply about two percent of total global energy demand.

The wind energy industry, for example, has grown in just two decades from a producer of small machines for remote power applications, to a modern, multi-billion-

Global Generating Capacity of Non-Hydro RETs

Technology	Installed Capacity (MW)
Biomass	35,000
Geothermal	9,000
PV	1,200
Solar Thermal	350
Wind	14,000
Total	59,550

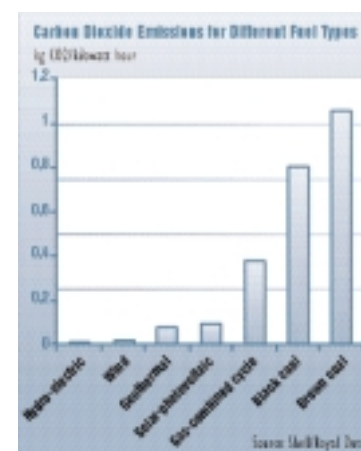
Figures are for year 2000 and approximate. Source: UNEP

dollar industry supplying bulk, grid-connected power. At the beginning of the 21st century, 14,000 megawatts (MW) of wind turbines generate clean electricity in more than 30 countries. The evolution of the wind energy industry has far exceeded even the most optimistic 1990 European Union prediction that 5,000 MW would be installed by the year 2000. Consequently, the cost of wind-generated electricity has dropped seven-fold, which makes windpower competitive with most fossil fuel technologies.

The modern wind energy industry evolved rapidly due to a combination of government support, sufficient research and development, and policies that created a market for wind-generated electricity. This successful model provides valuable experience for the development of other RETs (see Part 2: Frameworks for Success).

Advantages and Limitations of RETs

Renewable energy technologies are first and foremost the cleanest options for producing energy and eliminating greenhouse gas emissions. But there are many other advantages. These include energy, economic, and environmental security.



Energy Security

RETs can diversify the energy supply, thereby promoting energy security and price stability. For some nations, RETs can reduce dependence on imported fuels, an issue that is particularly important for developing

countries. RETs can also promote energy security by decentralising energy supplies with smaller, modular, and rapidly-deployable energy projects that are particularly suited to the electrification of rural communities in developing countries.

Economic Security

RETs are often the most economical choice because of their *scale*. Their modular nature means they can be built (and paid for) as the demand for energy grows, and embedded within an existing network, if there is one. By contrast, large, centralised energy systems take much longer to build and are normally designed to supply a future demand that may not eventuate. The vulnerability of central power plants and transmission lines to power interruptions is also important. In the United States, for example, power interruptions cost as much as \$80 billion annually.⁶

For developing countries, the energy security provided by RETs makes them attractive in rural areas, while simultaneously offering a clean “leap” over fossil fuels. The modular and distributed nature of RETs can also reduce the need for upgrading electricity distribution systems, or for expanding distribution or transmission capacity.

RETs can also provide regional and local job opportunities, particularly in rural areas. This can contribute to the

stability of local communities, which then slows urbanisation—a particular problem for many already overcrowded cities in developing countries. In addition, if energy is locally produced, money is invested in the local community and not exported, although RET products and services can be exported. All of these impacts can create an increase in local tax revenues, which can then create a more diversified tax base.⁷

In terms of electricity generation, RETs are more employment intensive than fossil fuel or nuclear



Installation of wind turbines can provide significant new employment, as well as clean energy. (Photo: Nordex)

options. The employment potential of RETs can be clearly seen in the wind energy industry. According to a survey by Danish wind energy manufacturers, 17 worker-years are created for every megawatt of wind energy manufactured, and five worker-years for every megawatt installed.⁸ In the year 2000, the wind energy industry provided more than 85,000 jobs worldwide and could provide up to 1.8 million jobs by 2020.⁹

RETs are up to three times more employment-intensive than fossil fuel power options: 188 worker-years are created locally for every megawatt of small solar electric systems.

In Germany, windpower accounted for 1.2 percent of electricity generation in 1998 and the industry employed 15,000 people, compared to nuclear with a 33 percent share and about 40,000 jobs, and coal with

Limitations of RETs

The major limitation of RETs lies in the intermittent and site-specific nature of the energy source. Solar cells, for example, generate electricity only when light is available, and wind generators operate only when there is sufficient wind. However, even though such resources are intermittent, they are often highly predictable.

In terms of electricity, most modern grid systems can absorb up to about twenty percent of their capacity from intermittent generating sources such as wind. Even this limitation can often be overcome with the right mix of technology. For example, wind energy and photovoltaic systems, when combined with some form of energy storage such as a hydropower reservoir, can provide a much higher percentage of electricity in a grid system. Biomass energy systems can often be fuelled by crops harvested on a continuous basis, and solar water heaters can store heated water in a tank for later use.

Another key issue that can limit RETs is the need to establish trained support where RETs are installed. Past experience has shown that many failures have resulted from lack of maintenance or inappropriate operation.

RETs are also at different stages in their development and therefore may have technical limitations. Many of these limitations, however, can be overcome with further research and development.

Energy Efficiency: The Enabling Choice

About 60 percent of primary energy initially recovered or gathered is lost or wasted during various stages of conversion. About 60 percent of the remaining energy is again lost or wasted at the end-use stage. This means that almost three-quarters of primary energy is wasted or rejected before it does any productive work. Capturing this wasted energy is both economically and environmentally desirable. Improving energy efficiency is often the “enabling path” that allows renewable energy technologies to be economically competitive.

For example, a modern compact fluorescent light globe (CFL) is four times more efficient than an incandescent bulb, and much cheaper to run over its useful life. However, it is the reduced electricity demand needed to power the bulb that actually economically enables the compact fluorescent light to be part of a photovoltaic (PV) system (see Solar Photovoltaic Electricity).

A small PV panel can supply sufficient energy to run a 20 watt CFL, but this same panel would run a standard 75 watt incandescent lamp (which produces the same amount of light) for only one-fifth as long. Five PV panels would be needed to run the incandescent for the same amount of time as the CFL. For rural households in developing countries, the PV-CFL combination offers the benefit of electric lighting with a much lower capital cost than most other options, including a transmission grid. The PV-CFL system is five times more efficient than PV with incandescent bulbs, 100 times more efficient than a kerosene lamp, and 500,000 times more efficient than candles—without creating indoor pollution. Consequently, it is a superior alternative to both capital-intensive and low-tech options.



These 50-watt PV systems, installed in homes in a Brazilian village, provide electricity for lighting and other energy tasks. Such systems are often the cheapest option for providing energy services. (Photo: Roger Taylor, courtesy NREL)

a 26 percent share and 80,000 jobs.¹⁰ Based on a market share comparison, the potential to create jobs is far greater for wind than for coal and nuclear options.

Several other studies show that up to 188 worker-years are created locally for every megawatt of small solar electric systems. These jobs come primarily from the

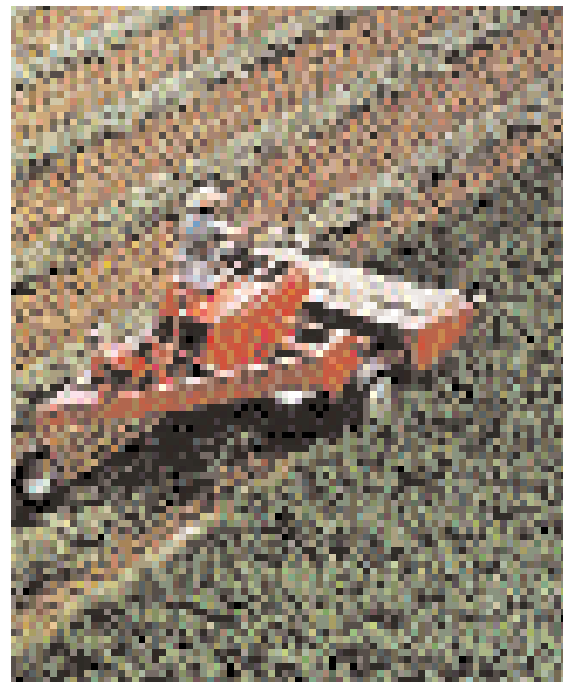
local retailing, installation, and maintenance of systems. Local production of solar modules can also contribute to a country's manufacturing infrastructure. RETs can thus contribute to the creation of local industries—a priority in any economic development strategy.¹¹

Environmental Security

In addition to much lower greenhouse gas emissions, RETs offer other direct environmental benefits, particularly to developing countries. Improved air quality can be achieved through lower airborne emissions of pollutants compared to traditional fossil fuels. In particular, indoor air quality can be improved by substituting technologies such as photovoltaics (PVs) for lighting instead of burning kerosene. In many regions where a shortage of potable water damages human health, water supplies and water quality can be improved using small hydro-electric schemes. Solar pumps and small wind pumps can also be used to obtain water from underground sources.

Growing energy crops, such as fast-growing trees, (particularly in areas that overproduce food crops) can reduce soil erosion. Often, these energy crops require lower levels of agricultural chemicals and can be grown on land degraded by previous agricultural practices. This can help to improve soil conditions and enhance wildlife diversity.

The following section provides an overview of current and emerging renewable energy technologies.



Energy crops and crop residues can be converted to many forms of bio-mass energy. (Photo: Northern States Power)

Of all the new renewable energy technologies, generating clean electricity from the wind has made the most significant commercial progress. The wind energy industry has evolved, in just two decades, into a modern, multi-billion-dollar industry supplying power in 30 countries. At the beginning of the 21st century, 14,000 MW of wind turbines generate enough clean electricity to power the equivalent of 14 million modern households.

Today, windpower in good wind sites is much cheaper than nuclear power and competitive with all forms of fossil fuel power generation, with the exception of advanced gas turbines. Even this barrier will soon be broken if windpower continues its current technical and economic progress.

The Technology

A wind turbine converts energy in the wind into electrical energy, or into mechanical energy for pumping water or grinding grain. The most common wind turbines in operation today have two or three blades revolving around a horizontal axis. These “horizontal-axis wind turbines” (HAWT) also include a gearbox and generator, a tower, and other supporting mechanical and electrical equipment (see diagram next page).

The total available and technically recoverable wind resource in the world today is equivalent to four times the world's total electricity consumption in 1998.

Wind turbines are rated by their maximum power output in kilowatts (kW) or megawatts. For commercial, utility-sized projects, the most common turbines currently sold are in the range of 600–1,000 kW. These are large enough to supply electricity to 600–1,000 average modern homes. A typical 600 kW turbine has a blade diameter of 35 metres and is mounted on a 50-metre concrete or steel tower. The newest commercial turbines, however, are rated at 1.5–2.5 MW. Generally, all wind turbines produce, on average, power equal to 20–30 percent of their rated capacity. For village or smaller commercial applications, wind generators are available in sizes ranging from a few hundred watts to 100 kW.

The power that can be generated from a modern wind turbine is, in practical terms, related to the *square* of the windspeed (theoretically, the energy is related to



(Photo: Warren Gretz, courtesy NREL)

the cube of the windspeed). This means that a site with *twice* the windspeed of another site will generate *four times* as much energy. Consequently, the availability of good windspeed data is critical to the feasibility of any wind project. Data is usually gathered with anemometers installed at a prospective site. One year of good data is usually the minimum amount needed to assess the site's potential.

Most commercial wind turbines operating today are at sites with average windspeeds greater than six metres per second (m/s) or 22 km/h, although some commercial sites have average windspeeds as low as five m/s (18 km/h), and a prime wind site will have an annual average windspeed in excess of 7.5 m/s (27 km/h). Utility-sized commercial wind projects are usually constructed as windfarms with several turbines

Key Points:

- Wind is a mature and modular technology for both grid and stand-alone applications.
- The wind resource is intermittent, but highly predictable, if measured over a sufficient period of time.
- Commercial wind sites generally have an average annual windspeed greater than six metres per second.
- Commercial wind turbines for grid applications range from a rated capacity of 100 kW–2 MW and average 700 kW, while wind turbines for small, stand-alone applications range from 50 W–100 kW.
- Possible environmental issues include noise, visual, cultural, land use, and fauna impacts.
- A wind turbine will produce on average 20–30 percent of its rated capacity.

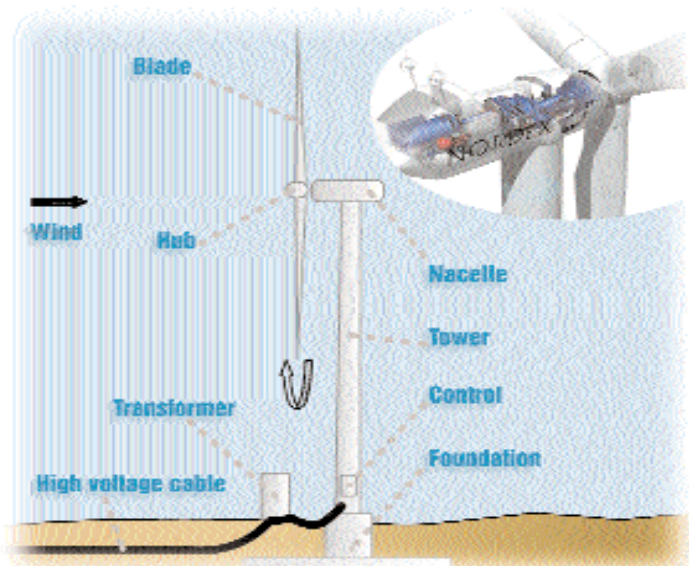
erected at the same site. Wind projects have been successfully built to power a wide range of applications in diverse and often extreme environments.

Some of the newest windfarms are being placed in shallow, offshore areas where environmental impacts are often lower and the availability of a steady, non-turbulent wind flow allows turbines to operate more efficiently and produce more power. Denmark has already installed over 100 MW of offshore wind turbines, while the United Kingdom and the Netherlands are planning major projects.

The feasibility of a wind project can be influenced by access to the electrical grid. The need to install or upgrade high-voltage transmission equipment can significantly add to the cost of a wind project. However, the newest variable speed wind turbines can help stabilise electrical grids in remote locations.

For off-grid and mini-grid applications, wind generators can be combined with diesel generators or other energy sources, as well as batteries or other storage devices. For applications other than electricity, windmills continue to be a proven and reliable technology for pumping water.

Wind turbines are also a *modular* technology, which means they can be installed as a utility needs the capacity. A small windfarm can generally be constructed within a year, once planning approval is received. Planning permission to construct a wind turbine or windfarm is generally based on an environmental impact assessment that can identify and mitigate visual, noise, land use, cultural, or fauna impacts.



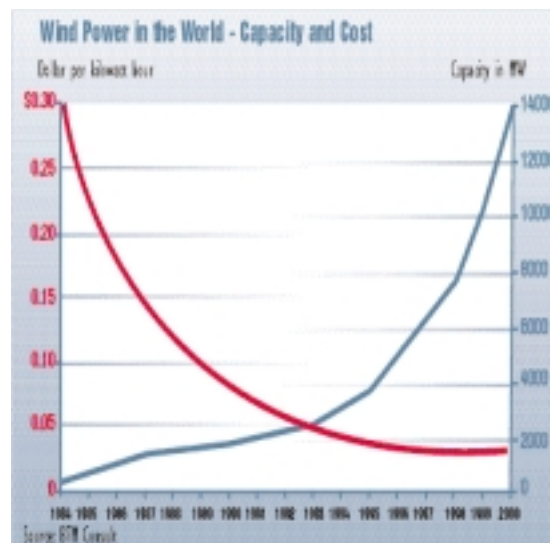
Components of a typical wind energy system. (Diagram insert: courtesy Nordex)

The Industry and Market Trends

Throughout the 1990s, the wind energy industry grew by 15–20 percent per annum, and by almost 30 percent during the period 1997–2000. This substantial growth is expected to continue at least for the first few years of the 21st century, with about 4,000 MW of new capacity added in the year 2000. Estimates by the World Energy Council put the installed wind capacity in 2020 at between 180,000 MW and 474,000 MW, some 18–47 times the installed capacity at the beginning of the century. However, if growth can be maintained at the 30 percent rate, more than 1.2 million MW would be installed by 2020, which would meet 10 percent of the world's electricity needs.

Since the current phase of development began in the 1980s, the price for wind-generated electricity has been reduced by an average of three percent per annum, and is predicted to be approximately \$0.03 per kilowatt-hour (kWh) by 2020, making wind competitive with all forms of fossil fuel generation. There is considerable interest in offshore developments, particularly in Europe, where Denmark plans to generate 750 MW from offshore windfarms by 2005.

Ten major international manufacturers currently produce 97 percent of all wind turbines in sizes and models ranging from a few hundred watts to several megawatts. Since windspeed increases with greater height above the ground, major manufacturers are developing even larger machines on taller towers with an expected technical limit of about five MW during the next two decades.



Photovoltaic (PV) devices, also called “solar cells,” are a rapidly evolving renewable energy technology. Solar cells were first used for applications in space before entering terrestrial niche markets in the early 1980s to power telecommunications equipment and consumer devices, such as watches and calculators.

At the beginning of the 21st century, some 400,000–800,000 photovoltaic systems have been installed to power everything from large grid-connected power stations and roof-top residential systems, to small-scale, stand-alone units for rural use. PV is currently most economically competitive in remote sites away from electricity grids, and where only relatively small amounts of power are required—typically less than 10 kW. However, the market for residential and commercial grid-connected systems is growing rapidly as costs decline.

For rural villages in developing countries, PV technology offers an immediate, direct, and safe alternative to kerosene lamps and diesel generators.

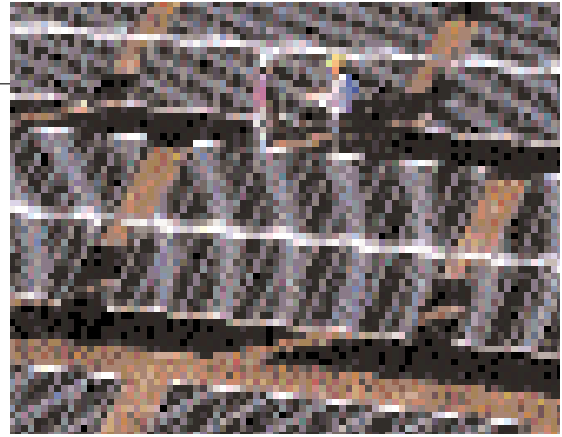
The Technology

Photovoltaic devices are semiconductors that convert solar energy directly into electricity. Although there are about 30 different types of PV devices under development, there are three main technologies in commercial production: monocrystalline cells, polycrystalline cells, and thin-film cells.

Monocrystalline (single crystal) solar cells are manufactured from a wafer of high-quality silicon and are generally the most efficient cells for converting solar energy into electricity. *Polycrystalline* solar cells are cut from a block of lower-quality multicrystalline silicon and are less efficient, but also less expensive to produce. *Thin-film* solar cells, manufactured in a process similar to tinting glass, are made of semiconductor material deposited as a thin film on glass or aluminium. Thin-film solar cells are generally only half as efficient as mono and polycrystalline cells, but they are much cheaper to produce and widely used to power consumer devices such as watches and calculators.

Solar cells are encapsulated into *modules* that are often combined to form an *array*. There is, however, a growing market for “building-integrated” PV devices that are manufactured as part of conventional building materials, such as roof tiles or glass panelling.

A PV array is usually part of a *system* that may also include energy storage devices (usually batteries), support frames, and electronic controllers. These are collectively referred to as the *balance-of-system* (BOS) components.



These PV panels feed solar electricity directly into the grid. (Photo: Sacramento Municipal Utility District, courtesy NREL)

The amount of power from a PV array is directly proportional to the intensity of the light hitting the array. Even on cloudy days, PV systems can still provide electricity as long as there is some solar radiation.

Photovoltaic arrays produce direct current (DC) electricity, but the power can be regulated using electronics to produce any required combination of voltage and current, including conventional residential alternating current (AC). PV is a modular technology that can be used in most parts of the world, and integrated with diesel, wind, and hydropower systems.

The size of a typical PV system varies from 50 W–1 kW for stand-alone systems with battery storage; from 500 W–5 kW for roof-top residential grid-connected systems; and from 10 kW–1MW for ground-based grid-connected systems and larger building-integrated systems.

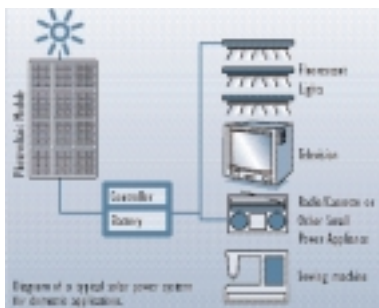
Photovoltaic modules are solid state devices with no moving parts and a demonstrated record of durability and reliability. PV modules may operate for up to 30 years and are generally sold with 10–20 year manufacturer warranties. Although PV modules themselves require little maintenance, other BOS components may require more maintenance, particularly batteries.

Key Points:

- PV technology is evolving rapidly and is most competitive in remote sites, far from electricity grids, and when relatively small amounts of power are required—typically less than 10 kW.
- PV is a modular technology that can be used in most parts of the world and integrated with other technologies including diesel, wind, and hydropower systems.
- PV systems generally have high capital but low running costs.
- PV has few environmental risks. Planning approvals and environmental assessments are generally not necessary.

To assess the value of electricity from a PV system (and other systems using renewable energy as a primary energy source), it is necessary to compare the cost of the PV system to the minimum cost of providing the same energy service by an equivalent alternative. This is particularly relevant for stand-alone systems in remote areas where comparisons between PV and other energy supply options should be based on running costs (i.e., fuel, maintenance, depreciation, interest, etc.) and not simply capital costs.

This is because PV systems generally have a high capital cost, but a low running cost, as the “fuel” is sunlight. In many countries, for example, a solar home system to power lights and small appliances can be purchased for as little as \$350,¹² while a grid extension or a diesel generator would cost much more.



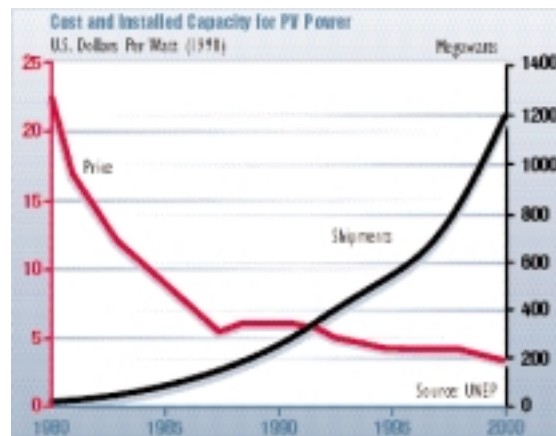
The Industry and Market Trends

The PV market grew by an average of 15 percent annually during the 1990s, a growth rate that is expected to continue as costs decline and new markets open up, particularly the market for grid-connected PV systems. In 1999, 200 MW of PV modules were sold for a total revenue of about \$1 billion. The total installed capacity worldwide is now about 1,200 MW with an average cost of approximately \$4 per watt.

There are at least 30 firms worldwide that fabricate PV cells and many more that assemble these cells into modules. The increasing mass production of PV technology continues to reduce costs in line with the classic “learning curve” for new technologies. In the period since 1975, costs have been reduced by 20 percent for each doubling of cumulative sales.

There is a general consensus among PV engineers that thin-film technologies offer the best long-term prospects for very low production costs. In the near-term, however, crystalline technology still has a large potential for cost reduction through economies-of-scale and technical improvements. Current research and development is aimed at improving both the cell and module efficiencies and reducing the cost for BOS components, which currently make up half the cost of most systems.

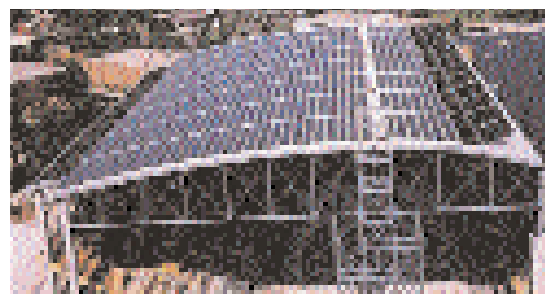
If present trends continue, the PV market is expected to reach 1,000 MW per year by 2010 with costs around \$1.50 per watt. However, if a growth rate of 30 percent can be maintained, 15,000 MW of PV will be installed and this will drive the cost to between \$0.06–0.15/kWh.¹³



Unlike many other power technologies built in larger capacities (including other RETs), the smaller size of most PV modules means the technology is inherently consumer-focused. Thus, the value of PV systems—and the point at which the technology becomes competitive with other options—is very different from the standpoint of the consumer than that of the bulk power producer or electricity retailer.

In new competitive electricity markets promoting embedded generation, for example, there is a growing trend toward “net metering.” In this process, a customer connecting a PV system to an electricity grid is paid the same price for the electricity “exported” to the grid as for electricity “imported.” In such markets, PV does not compete against the *wholesale* price of electricity but against the *retail* price, which is much higher.

There are a number of national marketing initiatives to increase the penetration of PV into traditional markets. Japan has a target of 4,600 MW of installed PV capacity by 2010, consisting mainly of residential grid-connected systems supported through a gradually reducing subsidy of 50 percent combined with net metering. In the US, the “Million Solar Roofs” initiative aims to install one million solar hot water and PV systems by 2010, using partnerships between local and federal agencies. Germany aims to achieve 100,000 grid connected PV systems by 2005 using interest-free loans and a small capital subsidy of 12.5 percent. The European Union as a whole has established a 2010 goal of 3,000 MW of PV capacity from 500,000 grid-connected PV systems on roofs and facades within the EU, and from another 500,000 systems for decentralised electrification in developing countries.



PV can be integrated directly into building components, such as roofing materials. (Photo: Craig Miller Productions, courtesy NREL)

Bioenergy is derived from *biomass*, a term that generally refers to any plant or animal matter. Bioenergy in the form of heat or electricity can be produced by using biomass directly as a fuel, or as a feedstock to produce biogas and other biofuels.

Burning and using biomass accounts for about 15 percent of global primary energy use and 38 percent of primary energy used in developing countries, mainly in the form of firewood for cooking and heating. Often, this firewood is taken from forests in an unsustainable way. In this document, only the sustainable and more commercial uses of biomass resources are described.

The Technology

The main sources of sustainable biomass include:

- *industrial and agricultural wastes and residues*, such as sugar cane waste (bagasse), wood waste from forestry operations, and residues from other short rotation crops such as straw and husks
- *organic wastes* from animal husbandry
- *energy crops*, such as sugar cane, corn, and trees grown in short-rotation plantations
- *domestic and municipal wastes*, such as sewage and garbage¹⁴

The main processes for utilising these sources of biomass include:

- *direct combustion*, usually of solids, in boilers or as a fuel in engines or turbines
- *gasification*, via a physical or chemical conversion process to a secondary gaseous fuel, followed by combustion in an engine, boiler, or turbine
- *biological conversion*, via bacterial anaerobic digestion to methane-rich biogas that is used as a gaseous fuel
- *chemical or biochemical conversion*, to produce methanol, ethanol, or other liquid fuels

Many combinations of sources, processes, and technologies are possible, but direct combustion is the most fully-developed process.

Bioenergy projects can often be designed to generate both heat and electricity, which increases the overall efficiency and financial viability of a project. Such projects may also create a cost-effective solution to the disposal of wastes that may otherwise become potential environmental problems.



Residue from crops can be gasified and combusted to provide heat and power. (Photo: Warren Gretz, courtesy NREL)

Bioenergy projects can be built in a wide range of sizes. At the upper end of the scale, they can be as large as 100 MW power stations that generate both electricity and heat. Bioenergy projects can also be small enough to produce lighting and cooking energy for a single household or village. At this level, one of the most common technologies fueled by biogas is a cook stove.

At the power project level, about 7,000 MW of electricity from biomass-fired projects is currently fed into the US national electricity grid. Many biomass power projects, however, operate on steam-turbine technology first introduced about 100 years ago. Often, these plants have a low conversion efficiency that can be significantly improved.

The largest biomass programmes to use energy crops are the US programme to produce ethanol from corn (four billion litres in 1999), and the Brazilian programme to produce ethanol from sugar cane (14 billion litres in 1999).

Key Points:

- *Biomass is a widely distributed but variable resource that can be converted to bioenergy in the form of heat and electricity.*
- *Bioenergy can be produced in a wide variety of processes using a number of technologies to meet both large and small-scale needs.*
- *Biomass is renewable and carbon-neutral, but only if it is grown at the same rate it is harvested.*
- *Biomass resources may not be sufficient to ensure a continuous supply, as availability is influenced by natural events such as weather.*
- *Political pressures to reduce atmospheric carbon emissions may create new market opportunities.*

The keys to an economically viable bioenergy project are the type, amount, accessibility, and cost of the biomass resource. Projects are generally more cost-effective when waste products from some production process are used, such as bagasse or sawmill residues. For many bioenergy applications, however, big is not necessarily better, as transporting biomass fuel or feedstock over large distances decreases the economic viability of the project.

In addition, some agricultural wastes are available only during certain times of the year, and may have to be stored if they are to be used as a continuous fuel. This can be difficult, expensive, and require special equipment or storage facilities. An alternative to storing biomass is to use other fuels, such as natural gas or alternative biofuels, during these periods. This may allow a more efficient, continuous, and profitable operation, but will also usually increase the project's capital investment.



Briquettes made from firewood are a common biomass fuel in many developing countries. (Photo: Roger Taylor, courtesy NREL)

Intermittent availability of a biomass resource is currently an issue for many bagasse-fired electricity plants that operate only during sugarcane harvesting periods. However, one outcome of liberalising electricity markets in some countries has been a new economic opportunity for biomass project developers to invest in facilities and equipment that are able to generate a higher level of “firm” or continuous power. Consequently, these developers can generate higher revenues.

Energy systems powered by biomass have several potential environmental advantages and disadvantages. Biomass resources are renewable, but only if the resource is harvested at the same rate it is grown and soil nutrients are not depleted. Such resources are also carbon-neutral, meaning they absorb as much carbon from the atmosphere when growing as is released when they are combusted.

This advantage makes further bioenergy developments less risky in a global political climate that increasingly favours carbon reductions. There may also be economic advantages if carbon-trading schemes become a prominent means of meeting carbon reduction targets. In addition to these potential greenhouse gas abatement benefits, good bioenergy projects can address many other secondary issues such as soil erosion, habitat diversity, nitrogen run-off, and the protection of watersheds.

One of the potential disadvantages of bioenergy projects can be unsustainable impacts on soil and water resources. The inappropriate selection of species or management strategies, for example, can lead to land degradation. Impacts on air quality may also be a potential issue for combustion-type bioenergy projects, and may require lengthy environmental assessments before such projects can be approved. The use of energy crops to produce methanol, for example, requires pre-treatment of feedstock, its conversion to a gas, and a process to remove contaminants from the gas before the final conversion to methanol. However, the correct selection of plant species can also result in the profitable production of energy crops in marginal or degraded areas. Additional environmental benefits may include increased food crop yields and decreased fertiliser use.

Other issues that may influence the viability of a bioenergy project—particularly larger projects—include competition for land use, public resistance from proposed land use changes, and the complexity of coordinating a range of activities and institutions (farmers, utilities, transport companies, etc.). For these reasons, an intensive planning and management process is usually required, which may need to address these issues at both the local and national levels.

The Industry and Market Trends

Biomass has great potential to increase its contribution to commercial energy production. By some estimates, biomass could increase its current share of the energy mix by two-and-a-half times and contribute nearly 50 percent of the world's energy. Sweden, for example, plans to increase biomass energy production from 20 to 40 percent by 2020 through extending and improving the use of residues from forest and wood processing industries.

The energy in falling water has been used by humans for thousands of years to crush or grind different substances. Modern hydropower developments, however, generally convert the energy in falling water to electricity.

The earliest hydro stations were often built as a part of large dam projects. Due to the size, cost, and environmental impacts of these dams (and the reservoirs they create), hydro development is increasingly focused on small-scale projects. Although the definition of *small-scale* varies, only projects that have less than 10 MW of generating capacity are considered here. This definition also includes mini-hydro (<1 MW), micro-hydro (<100 kW), and pico-hydro (<1 kW).

The Technology

Generating electricity from falling water involves a well-proven but very site-specific technology. The main components of a small-scale hydro (SSH) system are the turbine and the generator. Other components include the physical structures that direct and control the flow of water, mechanical and/or electronic controllers, and structures to house control equipment.

There is great debate whether hydro schemes with large dams should be considered renewable. Large dams generally flood significant areas of land, radically change the pattern of river flows, and can displace entire communities.

The amount of energy in water stored behind a dam which can be converted to electrical or mechanical energy depends on the vertical distance the water drops (the “head”) and the volume of the water. For example, 100 cubic metres of water falling 10 metres (a typical low-head application) represents the same energy potential as 10 cubic metres of water falling 100 metres (a high-head application).

There are several different types of turbines for hydro applications, and the optimum choice depends strongly on the available head and the volume of water. Generally, a site with greater head will require smaller, less expensive turbines and associated equipment.



An 800-kW micro-hydro facility provides electricity to a remote town of 700 people. (Photo: Duane Hippe, courtesy NREL)

For most hydro projects, water is supplied to the turbine from some type of storage reservoir, usually created by a dam or weir. The reservoir allows electricity to be generated at more economically desirable times—during periods of peak electrical demand, for example, when the electricity can be sold for a higher price. In these systems, the amount of electrical power that can be generated is determined by the amount of water that is stored and the rate at which it is released.

The most environmentally attractive hydro system is a “run-of-river” system that does not substantially change the amount of water that normally flows in the river or stream. Such a system may use a special turbine placed directly in the river to capture the energy in the water flow, or a small weir to divert water into a turbine. A conventional SSH plant may also operate as a run-of-river system if the natural variability of the river flow is maintained. However, this type of plant generates less power during times of low river flow.

Key Points:

- *Hydro is a mature, well-proven, but very site-specific technology.*
- *The amount of power in falling water is related to the height of the fall and the volume of water.*
- *Systems can often be installed at existing weirs and dams, which can reduce costs.*
- *Environmental assessments are essential to obtain planning and construction permission.*
- *Systems can have both negative and positive local environmental impacts.*
- *Hydro systems generally have a long life and high reliability.*
- *Well-planned systems generally have minimal environmental impact when operating.*

Small-scale hydro systems are modular, and can generally be sized to meet individual or community needs. However, the financial viability of a project is subject to the available water resource and the distance the generated electricity must be transmitted.

Hydro systems do not create any pollution when they are operating, and generally provide highly reliable power. They also have very low running or maintenance costs, and they can be operated and maintained by locally-trained staff.

Hydro systems generally have a long project life. Equipment such as turbines can last 20–30 years, while concrete civil works can last 100 years. This is often not reflected in the economic analysis of power projects, where costs are usually calculated over a shorter period of time. This is important for hydro projects, as their initial capital costs tend to be comparatively high because of the need for civil engineering works.

Hydro developers generally need to invest in detailed analyses before a project can proceed. Regulatory authorities may require structures or systems that prevent adverse effects on flora and fauna, particularly fish. Conversely, some hydro systems may enhance local environments through, for example, the creation of wetlands.

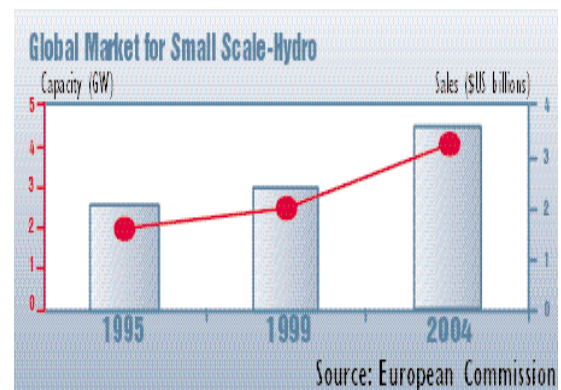
The Industry and Market Trends

Although significant potential exists for further SSH development, the availability of suitable new sites is limited, particularly if dams or other structures must be built, and where local land use and planning laws may limit such development. Worldwide, more than one hundred manufacturers produce small-scale

hydro equipment, although Europe and China have the most active industries. China alone has an installed capacity of 20 GW (20,000 MW) and is planning to install 1,500–2,000 MW per year in the period 2001–2005. Southeast Asia and Latin America are also promising markets.

In addition, a substantial number of weirs and other in-stream structures that already exist can be retrofitted with hydro equipment. About 3,000 MW of these low-cost applications are estimated to exist globally. As the civil works already exist, the additional environmental and land use impacts of these projects are often very small.

Although the technology is mature, there is substantial room for improvement. Electronic controls, telemetry-based remote monitoring, new plastic and non-corroding materials, variable speed turbines for use in low-head applications, and new ways to minimise impacts on fauna, particularly fish, are helping to make hydro systems more cost-effective and extending the range of potential sites.



The heat of the earth can be collected as geothermal energy and used for space heating, industrial process heat, and the generation of electricity. Geothermal energy has been harvested since the early part of the 20th century, although the use of geothermal energy resources has increased rapidly since 1970 and now occurs in more than 45 countries. About 9,000 MW of electricity is currently generated from geothermal resources, and about the same amount of geothermal energy is used for direct heating. The potential for geothermal electricity generation is about 120 times the current level.

The Technology

Commercial forms of geothermal energy are derived from low- and high-temperature hot water or steam recovered from wells drilled 100–4,500 metres below the earth's surface. In low-temperature applications, this energy can be used directly in a wide variety of end uses, including space heating and cooling for domestic and commercial buildings, and agricultural heating for greenhouses and fish farms. The technology is well-proven, relatively uncomplicated, and involves extracting energy via pumps and/or heat exchangers.

The direct use of geothermal energy has the advantage of offering a much higher efficiency—between 50 and 70 percent—compared to the 5–20 percent possible for the generation of electricity. Direct use applications can also draw from both high- and low-temperature geothermal energy resources, and can produce energy for about \$0.02/kWh. Low-temperature geothermal resources can also be recovered almost anywhere with special “ground source” heat pumps. These pumps can use the earth as either a heat source for heating, or as a heat sink for cooling, depending on the season.

For power production, high-temperature geothermal steam produces electricity through conventional turbine generators. However, these systems can cause adverse environmental impacts, such as sulphur dioxide emissions. Many of these impacts can be controlled with technology that “re-injects” waste gases or fluids into the geothermal well.



Geothermal power plant in California, USA. (Photo: Pacific Gas and Electric, courtesy NREL)

The Industry and Markets Trends

Total investment in geothermal energy from 1973 to 1995 was about \$22 billion, and the industry continues to grow at about 16 percent per annum for electricity generation and about six percent in direct uses. Currently, Costa Rica, El Salvador, Kenya, and Nicaragua generate 10–20 percent of their electricity from geothermal resources, while the Philippines generate 22 percent and plans to add 580 MW in the period 1999–2008. If present trends continue, geothermal capacity could increase from about 10,000 MW at the start of 2000, to 58,000 MW in 2020.

In direct uses, the market for ground-source heat pumps is growing rapidly. In the US, 300,000 domestic and commercial systems are in operation, and under a current incentive scheme, sales could reach 400,000 annually by 2005.

Key Points:

- *Geothermal energy is a well-proven and mature technology that can provide both heat and electricity.*
- *Geothermal energy resources exist in many areas of the world for both high- and low-temperature applications.*
- *Using geothermal energy directly for heating applications can be up to 70 percent efficient.*
- *Environmental issues associated with geothermal energy include emissions of sulphur and nitrogen gases.*
- *Environmental impact assessments are usually necessary before geothermal resources can be tapped.*

The sun's energy can be used directly to create both high-temperature steam (greater than 100° C) and low-temperature heat (less than 100° C) for a variety of heat and power applications. High-temperature solar thermal systems generally rely on collectors to focus the sun's energy. In low-temperature applications, solar energy is gathered using collectors made of various metal and synthetic materials. Solar energy can also be collected and used simply through the orientation and materials incorporated into the design of a building. This is referred to as *passive* solar design.

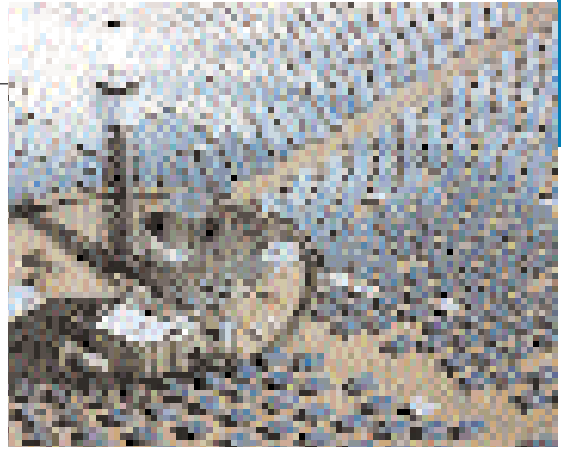
The Technology

High-temperature solar thermal systems use mirrors and other reflective surfaces to concentrate solar radiation. The resulting high temperatures can be used to create steam to either drive turbine electric generators, or to power chemical processes such as hydrogen production. Generating electricity from high-temperature solar thermal devices is already a technical reality. There is a small existing market, and costs are currently cheaper than generating electricity from PV for large grid applications. However, there has been only a small increase in the market for this technology over the past decade, and its long-term future depends on the success of further research and development.

Low-temperature solar thermal is cost-effective for a number of commercial and domestic applications. For generating hot water, flat-plate solar collectors made of metal or synthetic materials operate in a wide range of climatic conditions.

Low-temperature solar heat can be collected via *passive* or *active* systems. *Passive systems* are particularly suited to the design of buildings and solar hot water systems. Passive systems collect energy without the need of pumps or motors, generally through the orientation, materials, and construction of the collector which allow it to absorb, store, and use solar radiation. A passive solar hot water system generally uses flat plate collectors to heat water that “thermosiphons” into a storage tank situated above the collectors.

For new buildings, passive systems generally entail very low or no additional cost because they simply take advantage of the orientation and design of a building. In colder climates, a passive solar system can reduce heating costs by up to 40 percent while in hotter climates, passive systems can reduce the absorption of solar radiation and thus reduce cooling costs.



Solar Two in California, USA, uses tracking mirrors to focus sunlight on a central boiler: The high-temperature steam is used to drive an electric turbine. (Photo: Sandia National Labs, courtesy NREL)

The most common *active systems* use collectors and a pump to circulate water or another heat absorbing fluid. For domestic applications, the solar hot water system (SHS) is a mature technology that can provide domestic hot water. In Europe, a SHS can generally meet between 50–65 percent of domestic hot water requirements, while in subtropical climates, such as Asia and northern Australia, the percentage can be 80–100 percent of needs. A domestic SHS ranges in price from about \$500 –2,500.

The same types of solar collectors used in a domestic SHS can also be used for space heating applications. In some countries, such as Sweden, large district heating systems have been successfully built that heat large volumes of water during summer months for use in the winter.

The Industry and Market Trends

At the end of 1998, about 30 million square metres of solar collectors worldwide provided domestic and commercial hot water. In Australia, for example, five percent of domestic water heating comes via SHSs. The growth of this technology and its related industries, however, depends very much on energy policy. Experience in Australia and the Netherlands shows that major cost reductions are possible when production volume increases as a result of supportive policies and regulation.

Key Points:

- *Low-temperature solar thermal energy can be generated for space and water heating using mature technology.*
- *Active solar technology uses pumps and/or motors to circulate solar-heated fluid, while passive systems use the orientation and design of the solar collector to collect energy.*
- *High-temperature solar thermal technology for power applications is an existing niche market that needs further research and development to become competitive.*

There are a host of other RET technologies under investigation or in the early stages of commercialisation. These technologies may substantially change the way renewable energy is collected and used. These include marine-based RETs that generate power from waves, tidal currents, and ocean thermal gradients. Others include devices such as fuel cells and micro-turbines that can operate with renewable or non-renewable fuels. There are also a number of fossil-renewable hybrids that can be integrated into existing fossil fuel applications.

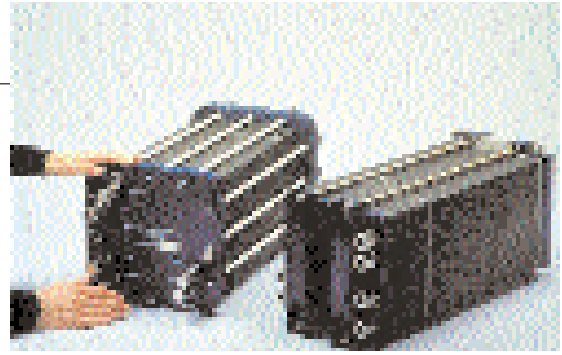
In the same way that just twenty years ago few people could forecast—or even imagine—the Internet revolution, there are bound to be technology surprises in the next twenty years. These innovations will most likely be the result of research and development.

Marine RETs

Although there are substantial marine energy resources, the corrosive, remote, and difficult nature of the marine environment makes extracting that energy more difficult than from land-based RETs. Generating electricity from the energy in waves is still experimental, and world capacity is currently less than one megawatt from a few small projects that use oscillating devices.

A new technology is under development to generate electricity from the movement of tidal currents in a manner similar to generating electricity from the wind. Tidal currents of 2.5 m/s (about 9 km/h) represent an energy density that is much greater than either wind or solar radiation. In this technology, bladed turbines are submerged in areas of high tidal current. The turbines are floating devices, fixed with anchors or mounted via a pole structure secured to the seabed.

This technology has been demonstrated on a small scale, and the first 300 kW demonstration project is due for operation in the year 2000. However, since the technology is developing in tandem with the use of offshore engineering techniques, it can be expected to develop quickly with appropriate research and development incentives.



The proton exchange membrane fuel cell is developing rapidly. The 13 kW cell on the right provides 2.3 times the power of the previous generation cell on the left. (Photo: Ballard Power Systems)

Fuel Cells

A leading contender for technological surprise is the fuel cell. With strong and well-funded research and development investment, and substantial partnerships between government and industry, the fuel cell is well placed to develop rapidly, perhaps more rapidly than many industry observers currently forecast.

A fuel cell works by combining hydrogen and oxygen in a reaction that produces electricity, heat, and water vapour. Although the fuel cell is not a renewable energy technology per se, it can certainly be a core element in a renewable energy system, particularly if the hydrogen comes from a renewable fuel or process, such as a bio-fuel or electrolysis via solar-generated electricity. In many ways, this type of system is the ultimate power source. Combining hydrogen and oxygen to produce electricity and heat, the “exhaust” from a fuel cell is simply water vapour. Put the reaction in reverse—use electricity from a renewable resource to split water into hydrogen and oxygen—and a complete, cyclic, and virtually non-polluting process can create both electricity and heat.

William Grove first conceived the idea of a fuel cell in 1839, some 40 years before the invention of the internal combustion engine. Today there are five basic technologies under development for both stationary and mobile applications.

For the automobile, the Proton Exchange Membrane (PEM) fuel cell is the current front-runner. Developed in the 1950s, PEM technology comes in various forms depending on the choice of fuel. All of them use a platinum catalyst, embedded in a membrane that acts as a solid

electrolyte. Unlike other fuel cell technologies, PEM cells have the advantage of operating at low temperatures, about 80° C.

Using special “reforming” technology, virtually any hydrogen-rich fuel can be used in PEM cells, including methanol, propane, natural gas, and gasoline. However, fuel cells with such reformers are more costly and complex than fuel cells using pure hydrogen.

About 30 companies are actively developing fuel cells, including all the major automobile manufacturers. The cost of fuel cells is on the same downward spiral as other RETs.

In automotive applications, major petroleum companies have recently teamed with fuel cell developers and the state of California in the US to initiate the California Fuel Cell Partnership. This program will road test 50 fuel cell vehicles, including 25 buses, between 2000 and 2003. Goldman Sachs Investment Research predicts the automotive industry will sell 40,000 fuel cell vehicles in 2004, with sales reaching 400,000 in 2008 and 2.5 million units by 2012—about five percent of annual vehicle sales.



Prototype fuel cell car. (Photo: courtesy NREL)

For stationary and commercial applications, the fuel cell may provide an equally lucrative market. A number of firms already offer commercial systems, and more firms plan to offer residential fuel cell systems in 2001. These systems will likely use a PEM fuel cell to produce both power and domestic hot water in a casing not much larger than a conventional hot water system. Further, the overall efficiency of this type of system is 50



Buses powered by fuel cells. (Photo: Ballard Power Systems, courtesy NREL)

to 100 percent *greater* than conventional methods. In these systems, excess electricity may also be exported into local power grids where, in new competitive markets, there is an increasing demand for cleaner “green” power (see Part 2: Frameworks for Success).

Renewable-Fossil Fuel Combined Systems

There are a number of combinations of RETs and conventional technologies that can offer many advantages during the transition to sustainable energy systems. They include:

- biomass co-firing of fossil fuel fired boilers and power stations
- solar reforming of natural gas into a number of gases with higher energy content that can be fed into conventional gas combustion technologies
- solar thermal steam feeding into existing fossil fuel boilers or power stations

These technologies are at various stages of commercial development, but may evolve rapidly if the correct market signals are provided.

Key Points:

- *The future holds many technology surprises—particularly if there is strong R&D support.*
- *Fuel cells are poised to become a major technology for both mobile and stationary applications.*
- *Some marine-based RETs could evolve rapidly due to their relationship with other existing RET technologies.*

“A successful future does not depend on future decisions but on the future of present decisions.”

— Heinz Rothermund,
Managing Director,
Shell UK Exploration
and Production

In the wake of new forms of competition and restructuring in the energy sector, it is worth remembering that our current energy systems are *not* simply the result of the market’s “hidden hand.” Government policies and incentives have created a framework favourable to the fossil fuel industries that dominate today’s energy scene.

Creating the Strategy

To create a sustainable energy future, we need a different framework. This framework will be most effective if it embraces a *sustainable energy strategy* that is deeply integrated into strategies for sustainable development. Further, national policies need to be internally consistent, harmonious with those of other countries, and conducive to private sector investment.

Such a sustainable energy strategy has two basic elements: the most efficient use of energy to create the necessary domestic, commercial, and industrial energy services (see sidebar); and the generation of primary energy from renewable energy sources. The most effective framework for this strategy is one that creates laws and standards where the market thrives in a “level playing field,” prices reflect the true cost of supply, and national social development goals are deeply integrated into the framework. Such a framework also accounts for the fact that the market can’t do everything, and that policies will sometimes be at odds with the aims of some stakeholders, including private enterprise whose major goal is the production of profit for shareholders.

Successful policies will vary, depending on the country, region, technology, and economic sector. There is no set of policies that will work for every country, and there are many examples of both “good” and “bad” policies. Policy development is also not restricted to the role of government. The private sector can and should develop and facilitate internal policies that reflect a move towards sustainable energy systems, and there is little doubt the private sector will play an increasing role in delivering meaningful energy services at the least cost, particularly in developing countries.

Barriers and Market Failures

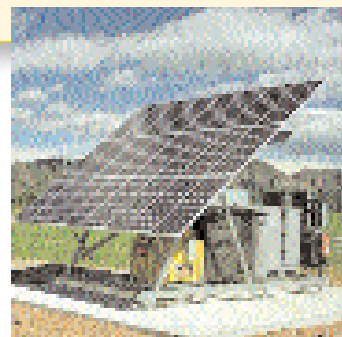
All new technologies face barriers. In the initial stages of development, *technical* barriers predominate, but even when these barriers are overcome, other *market* barriers may be even more formidable. Inconsistent energy pricing, lack of awareness and experience with new technologies, and lack of suitable institutional and regulatory frameworks are all substantial barriers to the commercialisation of new RETs. There are also some perceived social and environmental barriers resulting mainly from a lack of experience, but which can hinder public acceptance of a technology. The construction of a windfarm, for example, may be delayed or denied because of perceived visual impacts that are actually unfounded.

Choosing Energy Services

How do we get the energy services we want—cooked food, cold drinks, and comfortable buildings—in the most environmentally and economically efficient manner?

In developed countries, the 20th century model simply provided high-quality energy, often in the form of electricity generated from large, centralised power stations, which was then delivered through extensive transmission systems over large areas. Often, however, this model mismatched both the form and scale of energy needed to provide an energy service, and resulted in energy systems that were, and still are, inefficient. For example, heating water for domestic purposes to 70° C indirectly, with electricity from a distant power station, is often much less efficient than heating water directly using solar energy, gas, or wood.

With the advent of competition and new technologies, this model is shifting toward one where energy tasks are matched to the appropriate energy form, and at the correct scale. The model for the supply of electricity, in particular, is evolving into one that uses many generators embedded within a transmission network. Further, there are new market opportunities to supply energy services to people whether or not they are connected to an electricity grid—that is, to supply energy services “without the wire.” (See diagram on page 31.)



RETs can be integrated with other energy options. This PV/diesel hybrid system provides power in a remote area. (Photo: Warren Gretz, courtesy NREL)

Corporate Choice

Commerce is our most potent element of change, and essential to the shift to RETs. This shift will depend, to a large extent, on strong signals from the market that clean energy is a good investment. Governments can best provide these signals through consistent regulations that ensure the market delivers energy services in the most economically, environmentally, and socially responsible manner possible.

At the same time, the private sector can play a leading role through internal actions. For example, a number of multinational companies in the private sector are not waiting for government actions to increase their use of renewable energy. DuPont has made a commitment to source 10 percent of the company's energy from RETs by 2010, some 300 megawatts. Energy company BP has established a solar subsidiary and an internal carbon credits scheme to reduce its greenhouse gas emissions. Their competitor, Shell, has created an operating unit dedicated to marketing new RETs.

Despite substantial cost reductions, it is often noted that the largest barrier to greater renewable energy use is its price. This is only partially true, and ignores another major barrier to RETs: the large, persistent, and often hidden *subsidies* supporting fossil fuels that make them appear much cheaper than they really are.

Subsidies

Energy subsidies distort prices and generally impose a burden on both the economy and the environment. Energy subsidies can also decrease a nation's energy security by encouraging the use of imported energy, particularly petroleum.

The cost of environmental damage not reflected in the price of a good or service is referred to as an external cost, or "externality." Health effects, loss of biodiversity, damage to flora and fauna and, of course, climate change, are all external costs that at some point must be paid. In the European Union, the total cost of environmental damages from air pollution by fossil fuel power plants in 1990 has been estimated at \$70 billion, or 6.4 cents per kWh.¹⁵ Another European study, ExternalE, estimated that the external cost of carbon emissions was between \$4 and \$160 per tonne. If a very conservative figure of \$10–20 per tonne is used, the external cost of carbon emissions not currently included in the price is between 0.6–1.2 cents per kWh.

Direct subsidies to fossil fuel industries include payments from the public budget or forgone tax receipts. They have the effect of lowering the cost of energy production and consumption. Estimates of total world energy subsidies range from \$240–350 billion, or up to two percent of total world GNP. Annual subsidies to fossil fuels are estimated at \$72 billion, while nuclear fission receives up to \$14 billion.¹⁶ US subsidies for nuclear energy since 1947 have totalled \$144 billion, while solar and wind received \$5 billion.¹⁷

In the EU, total state aid to the coal industry between 1965 and 1995 was more than \$75 billion,¹⁸ while EU funding for nuclear energy was more than \$40 billion. In developing countries, average electricity tariffs during the first part of the 1990s were less than \$0.04/kWh, even though the average cost of supply was around \$0.10/kWh.¹⁹

There are also *hidden* or indirect subsidies. These include obligations to purchase a certain form of energy, reduced electricity rates for large (usually industrial) users, infrastructure support for industry (nuclear safety inspections, for example), and exemptions from risks or liabilities (such as the cleanup of contaminated sites, oil spills, or decommissioning of nuclear power plants).



RETs, such as this PV system, can offer a clean leap over fossil fuels in developing countries. (Photo: Jim Welch, courtesy NREL)

In one study of eight developing countries that together represent one-quarter of world energy use, the International Energy Agency found that energy subsidies in those countries cost \$257 billion in lost GDP— about 11 percent of the combined annual economic output of those eight countries.²⁰

Removing subsidies, however, is far from easy and if energy prices rise sharply, the impact is felt immediately, and often most painfully, by those least able to afford it. This can also create a potentially destabilising political situation.

SELCO

"The big challenge to any company trying to sell wireless solar power anywhere is getting people to understand it, and then getting them to realise that it is affordable and will provide sustainable electricity for lights, TV, radios, fans, and cell phones. People have to believe the government isn't going to get basic grid power to them anytime soon. This is the big problem: electricity is viewed as a public service, and rural families wonder why they can't have subsidies. And why not? Conventional rural electrification is usually subsidised, even today in the USA.

While maybe subsidies aren't the answer, financing certainly is, and government should help with that ... solar markets are often held back because governments promise free electricity, but when it's free, you don't get what you don't pay for! We say you can have free electricity and no power, or you can pay for solar power and have electricity..."

Neville Williams, President and Chair of Solar Electric Light Company (SELCO)



A PV panel, such as this one being installed on the roof of a building, can provide electricity to power lights and small appliances. (Photo: Ullal Harin, courtesy NREL)

However, there has been some progress on reducing energy subsidies, which have declined by 50 percent over the period 1990–1995.²¹ In China, where subsidies to coal industries were cut by \$14 billion, the economy still grew by 7.2 percent in 1998, while power plant emissions *dropped* by 3.7 percent.²²

Even if all subsidies were removed immediately, however, the existing infrastructure, much of which has been paid for with taxpayer funds, would still favour existing fossil fuel industries. The development of competitive energy markets and international trade in greenhouse gas credits may eventually address these subsidies, but the market has not yet consistently valued the environmental benefits RETs can provide.

When it is difficult to remove subsidies, one successful strategy is to provide equivalent subsidies to the RET alternative. As community support builds and people

recognise the practical alternatives, subsidies for fossil fuel options—and RETs—can be progressively removed.

Financial Barriers

RETs are often the most cost-effective choice for new energy services, but they may not be chosen due to factors such as lack of finance, lack of credible information, and/or lack of integrated planning procedures and guidelines. In particular, credit is an issue, as conventional credit arrangements may not fit well with specific conditions for investment in RETs, as they can be more capital-intensive and require larger up-front investments than conventional technologies. They may also require longer repayment periods. Investors, therefore, may prefer to invest in technologies with shorter repayment periods, thus lowering their long-term risk—even if those technologies are more expensive in the long-term.

A key challenge is the small-scale nature of an investment in RETs, which can drive investors to expect a more rapid return on capital. By contrast, large-scale investments in energy systems have usually been made by governments and large businesses, which accept lower rates of return. Many governments have also been prepared to subsidise some investments in order to attract additional development opportunities that new energy infrastructure may create.

In addition, rapidly evolving competitive energy markets—particularly electricity markets—have been notoriously short-term focused, favouring high discount rates that are disadvantageous to RET projects with high capital but low running costs. Due to their modular nature and relatively small size, RETs may also have high financing costs, as well as landlord-tenant-type split incentives between those who make energy decisions and those who bear the costs.²³ The cost of connecting to or using conventional transmission networks can also be high, and act as a financial barrier.

RETs are therefore often caught in a bind: financiers and manufacturers are often reluctant to invest the capital needed to reduce costs when the demand for RETs is low and uncertain, yet demand stays low because potential economies-of-scale are not available at low levels of production.

Financial institutions may also evaluate project applications with a RET component using a traditional framework that does not consider the full economic, social, and environmental advantages of RETs. Based on outdated or incorrect information, financial institutions often view these investments as too risky. RET projects are also generally smaller than conventional power development projects, typically ranging from \$500,000–10 million, which means they are often unable to tap international financial markets or other sources of private capital.

New moves to privatise infrastructure projects can also present problems for governments, particularly in developing countries. One of the goals of privatisa-

tion is to allow governments to exit the business of financing energy infrastructure and allow projects to be individually financed. However, the need for sovereign guarantees and long-term power purchase agreements has meant that the money for such projects comes from the private sector, yet much of the risk remains with the public sector. Given the limited amount of risk that any government can assume, RET projects are often unable to compete with other development priorities that receive sovereign guarantees.

A particularly significant obstacle for private companies who want to provide new energy supplies to rural areas is the high start-up costs of many options. Extending an electricity grid to a remote village, for example, can be very expensive, especially if only a few households are to be connected. Even when a grid is extended, the challenge isn't always getting villages to connect, but to use enough electricity initially to make the investment financially worthwhile. Although more energy is often available with grid extensions and expanded energy services are possible, people may take some time to change the way they use energy. This can be very costly for non-modular solutions such as grid extension, which have very high initial costs. Consequently, until more households join the network or use more electricity, the cost can be many times the typical cost in an urban area. RETs are similar. The installation of a solar electricity system for a single home can cost between \$350 and \$1,000—a large initial cost for someone whose annual income is less than \$2,000.

The problem is not necessarily that people are unwilling to pay for better energy services. In fact, people will spend a significant proportion of their incomes to improve their quality of life, or enable themselves to become more productive. In Bangladesh, for example, even the poorest people are connecting to the electricity grid when the service is available. In rural China, many people without easy access to cooking fuels are investing in efficient stoves and tree planting. The problem is that rural customers often cannot get affordable credit. This makes it difficult for them to pay high start-up costs to improve their energy supplies.

International Frameworks

The most significant international agreement for the energy sector is the United Nations Framework Convention on Climate Change (UNFCCC). Concluded in 1994 and since ratified by 175 countries, the Convention aims to stabilise atmospheric levels of carbon dioxide at a level that would “prevent dangerous anthropogenic interference with the climate system.” The Convention has a core principle of “common but differentiated responsibilities,” which means that all countries are responsible for protecting the atmosphere, but the major burden should fall on industrialised countries that have contributed the most greenhouse gases.

The Convention has since been modified by the Kyoto Protocol in December 1997. When ratified, the Protocol will bind specified countries to reduce aggregate greenhouse gas (GHG) emissions.

The Kyoto Protocol contains a number of mechanisms to help achieve emission reductions. These include the ability to trade GHG “carbon credits,” and undertake joint emissions reduction projects to the benefits of both countries involved. The three “Kyoto Mechanisms,” as they are called, differ somewhat, but are all intended to reduce the global cost of reducing GHG emissions while achieving other benefits for society.

Article 2 of the Protocol requires that developed countries promote, research, develop, and increase the use of renewable energy sources. This part of the Protocol also requires certain countries to progressively reduce or phase-out market imperfections, fiscal incentives, tax and duty exemptions, and subsidies in all GHG-emitting sectors that run counter to the objectives of the Convention.

Article 4 of the Protocol also requires developed countries to take steps to transfer environmentally sound technology to developing countries.

The Clean Development Mechanism does not specifically mention renewable energy but does require that any projects produce “real, measurable, and long-term benefits related to the mitigation of climate change.”

Transforming Markets

A **Renewables Portfolio Standard** requires that each electricity supplier provide a specified percentage of total electricity sales from RETs. This RET-based electricity must either be produced by the supplier or purchased (usually in the form of a credit) from another producer. The US federal government has proposed an RPS of 7.5 percent of the nation's electricity, from non-hydro power by 2010.

In the UK, the **Non-Fossil Fuel Obligation (NFFO)** came into effect in 1989, and at the same time the electricity industry was privatised. Although the measure was mainly to support the nation's nuclear industry, the NFFO did mandate 1,500 MW of electricity from renewable resources by the year 2000. The NFFO was established in several technology "tranches" to develop a portfolio of projects through a bidding process. The additional cost of new capacity was small and spread among all ratepayers, who paid less than 0.5 percent more for their electricity as a result.

Both measures use a combination of market and non-market forces to advance the commercialisation of RETs. A mandated target lowers the financial risk for project developers, and enables substantial movement along the "learning curve" to lower costs. If the target or capacity is auctioned or traded, there is a strong competitive pressure that can also lead to reduced costs. In the case of the NFFO, the average price declined 50 percent over the span of four auctions.

Although the NFFO did drive down costs, the actual capacity from new RETs was considerably less than in Denmark and Germany, where the guaranteed price of the **Electricity Feed Law** attracted more investment.

The use of **tradable certificates** in electricity generated from RETs is another market mechanism gaining momentum. In Australia, electricity suppliers are required by law to source a portion of electricity from RETs. Retailers can either purchase the electricity directly, or acquire certificates in an open market for RET-based electricity.

Creating a Level Playing Field

Clean energy competitors participating in evolving energy markets need fair competition. Creating this "level playing field" is achieved first through open, transparent, and appropriate regulation. Socially, regulation is an essential element that ensures access to energy services is extended to the entire population, and delivered via the most efficient and cleanest technologies.

Albert Einstein once observed that "things should be as simple as possible, but no simpler." Similarly, energy markets will advance the goals of sustainable development when sound regulation is simple, efficient, and free from undue bureaucratic interference.

Regulatory agencies must also have some flexibility in order to adapt to new market conditions and apply regulations that are sometimes outside the norm. The US National Rural Electric Cooperative, for example, found that in all the solar PV projects it analysed, the most important single success factor was a regulation requiring that all stakeholders be allowed to participate in the project's decision-making process.²⁴

Regulators can use several policy instruments to create markets where energy prices tell "the environmental truth." Unpaid external environmental costs—in essence, subsidies to existing energy forms that damage the environment—can be internalised via levies or taxes. Although this instrument has met strong resistance in some countries, environmental taxes are being used successfully in other countries, particularly in Europe. Carbon taxes, for example, are being used in Denmark, Sweden, and Germany to internalise the cost of greenhouse gas emissions.

These taxes are most effective if they are also part of an overall programme that shifts taxes away from economic "goods," such as labour, and onto economic "bads," such as pollution and resource depletion. This can be done in a way that is "revenue neutral," and that also recycles environmental taxes into pollution prevention. This realignment of the tax system is often referred to as "ecological tax reform."

Such taxes can overcome the market's failure to internalise pollution costs by *penalising* energy forms that are polluting, referred to as the "polluter pays" principle. Another policy tool is to *reward* producers of clean energy, either with a tax credit for new investment, or a production credit in the form of a payment for the amount of clean energy produced. The Danish wind energy industry is a good example of how a combination of appropriate tax policy and economic incentives created a functioning market and industry (see sidebar: The Danish Government Chooses Wind).

The Danish Government Chooses Wind

There is often an ideological debate about whether governments should “pick winners” among new industries, or let market forces determine the best option. In Denmark, the government decided that the country's own natural wind resources, and the potential for an export market, were sufficient reasons to fund the initial stages of a new industry. Less than two decades after that decision, the Danish wind industry is now larger than its fishing industry, formerly one of the nation's prime economic sectors. This impressive result contains a number of good policy lessons for other countries, and for the commercialisation of other RETs.

In the post-oil-embargo period of the 1970s, Denmark's infant wind energy industry was supported by a combination of various policy instruments, including subsidies. Danish policy first created a technological niche, and then a market niche, which has since developed into a functioning market. Danish manufacturers exported about \$1 billion of turbines and components in 1999, and have captured about 60 percent of the current global market.

The important factor in this market development was a flexible subsidy policy that could be adapted to suit changing economic, social, and technical conditions. The policy could also accommodate the specific requirements of invention, development, and diffusion during the entire innovation cycle. The main characteristic of Danish policy continues to be a strong link between wind energy policy and other policy areas, such as environmental and energy policy. These policies have a long-term focus, support R&D to create a knowledge base, promote financial participation by broad sections of the public, and induce energy suppliers to make a commitment to the expansion of wind energy.

Danish policy-makers also recognised that a continuous process of monitoring and evaluation was essential to success. The Danish experience demonstrates that policy instruments designed to trigger a technology leap, with subsequent economic and technical uncertainties, have been less successful than policy instruments that encourage a gradual approach where a new technology is continually improved in small steps.

With the introduction of energy taxes on carbon emissions, Denmark has achieved a partial internalisation of the environmental cost of power generation while improving the competitiveness of renewable sources. Moreover, the long-term national energy plan sets out specific goals for the expansion of wind energy and other renewable energy sources as substitutes for coal-fired power stations. After achieving the goal of supplying 10 percent of the nation's electricity from windpower by the year 2000, Denmark has set a new national goal of 50 percent by 2020.

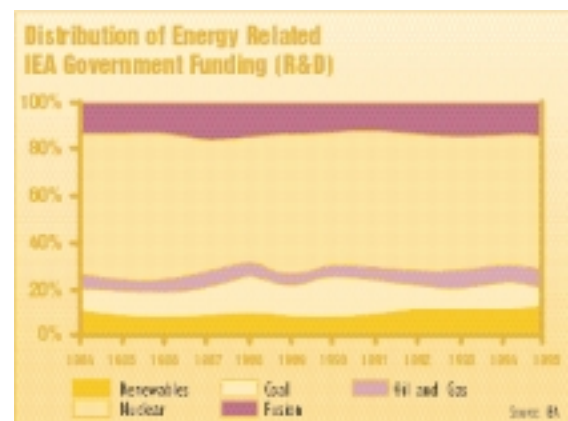
Regulatory agencies and governments can also expand the market for renewable energy through policies and programmes that mandate energy capacity derived from RETs. These *market transformation* programmes can be in the form of an *obligation* or *standard* such as the UK's Non-Fossil Fuel Obligation or the Renewables Portfolio Standard proposed for the US (see sidebar: Transforming Markets).

In the electricity sector, such programmes are greatly assisted when independent power producers are *guaranteed access* to electricity transmission networks. The US Public Utilities Regulatory Policy Act of 1978 (PURPA) requires utilities to pay favourable power rates to two groups of non-utilities: small power producers using RETs, and electricity producers using co-generation technologies. PURPA was among the first government regulations in the world to establish detailed rules for the connection and delivery of power from distributed generators to an electric utility, and has been the model for other regulatory approaches.

In the 1980s, more than 9,000 MW of non-hydro RETs were added to the US electricity supply as the result of PURPA. In Germany, the Electricity Feed Law guarantees prices for electricity fed to the grid from hydropower, biomass, wind, and solar electricity. In Italy, distribution companies are obliged to purchase energy from renewables while in Spain, electricity from RETs is charged at the long-term avoided cost of the distributing utility.

The Role of Research and Development (R&D)

Innovation has been, and will continue to be, an essential element in the development of sustainable energy technologies. Today's technology is the result of major funding during the 1970s when oil security was an important issue. Since oil security is not currently a driving issue (although prices have begun to rise substantially in mid-2000), the funding trends for RETs at the beginning of the 21st century are declining, precisely at a time when RETs are poised to make a much larger contribution. This is also due in part to the restructuring of the gas and electricity sectors, where the focus has been on projects with short-term commercial benefits. Between 1986 and 1996, for example, the total reported energy R&D spending in OECD countries decreased by 19 percent.



Matching Finance to Enterprise Development

“Our experience is that there are several distinct stages at which enterprises operate [see table]. The role of the finance community is to understand the distinct needs of these different stages, and to respond with financial instruments that apply appropriate terms and conditions. Thus the challenge of supplying rural energy services in developing countries is not the availability of technology, business models, capital, or the ability to pay; it is the mismatch between the needs of the enterprise and the types of financing currently available. That is, an entrepreneur who requires high-risk, early-stage capital and management hand-holding, will most probably not succeed in accessing the low risk corporate finance typically available to more advanced businesses.”—Phil LaRocco, E&Co Capital

Different Stages of Enterprise Development

	Stage 1: Small and very risky (e.g., <1000 solar home systems)	Stage 2: Medium size, still risky (e.g., 1,000-10,000 solar home systems)	Stage 3: Investment grade (e.g., > 10,000 solar home systems)
Strategy	Demonstrate the market	Build the brand	Scale-up
Sources of Finance	Own funds and seed capital	Risk capital	Later stage capital and debt
Investor Role (management)	Hand-holding	When needed	Arms length

Ironically, the estimated financial requirements to develop and commercialise new RETs are remarkably small—about \$8 billion to 2020. If renewables are to contribute as much energy as fossil fuels did in 1990, \$15–20 billion of R&D investment will be needed.²⁵ These are extremely modest sums compared to previous support for fossil fuels. The US government, for example, provided \$56 billion of public sector support for nuclear fission research and development from 1950 to 1993.²⁶ Funding to fossil fuels in the EU is still in the order of \$500 million per year, about four times the funding for renewables, which receive about \$130 million.²⁷ Shifting this funding to RETs will accelerate the process of R&D and commercialisation.

Although RETs are at various stages on their respective paths to commercialisation, and consequently require different types of R&D support, the “learning curve” for many RETs is similar to other new technologies. In the PV and wind industries, for example, each doubling of installed capacity has resulted in a price reduction of 20–30 percent.

It is a reasonable conclusion that further R&D investment in RETs will produce significant returns. However, the opposing need of the private sector to use their R&D funds to address short-term competitive pressures is currently set against the need of governments to fund long-term strategic programmes. This paradox can be resolved, in part, with new collaborative programmes and partnerships.

Such partnerships could be particularly helpful to developing countries, where the development of indigenous renewable energy sources could also bring other benefits, such as significant new employment. In Brazil, for example, the ethanol fuel programme employs about 700,000 workers in rural areas, while partnership programmes in India have created 100 new wind and PV manufacturing companies.

Frameworks for Finance

The combination of rapid economic growth in developing countries, continued economic growth in developed countries, and increasing population will most likely lead to greater demand for energy. Much of this increased energy demand will be in the form of electricity, and two-thirds of the projected new capacity will be built in non-OECD countries. Total projected annual power sector investments in developing countries are estimated to be between \$50–60 billion. Present annual global energy investments are approximately \$800 billion and energy investment between 2000 and 2020 is estimated at \$9–15 trillion.²⁸

RETs are the most cost-effective choice in many applications, but they are hindered by market barriers, including access to finance. There is little doubt, however, that the financial resources exist. Global capital resources are more than adequate to meet any potential demands coming from the energy sector, and these demands are unlikely to exceed 3–4 percent of global output—the same proportion that has prevailed for several decades.²⁹



RETs can provide regional and local employment opportunities. (Photo: Jim Welch, courtesy NREL)

Finance

There are many types of finance needed to fuel RET deployment, including:

Private Finance from personal savings or bank loans secured by private assets. This type of finance is concerned mainly with smaller companies and projects.

Corporate Finance, usually provided to companies that have a proven track record, and use balance sheet assets as collateral. Most mature companies use corporate finance.

Project Finance, used with distinct, single-purpose companies, whose energy sales are guaranteed by power purchase contracts. The robustness of these contracts, and their associated cash-flows, are key measures of interest to investors. Debt is generally a major component in project financing.

Participation Finance, similar to project finance but the number of investors is generally larger (a co-operative, for example). In these projects, local investors commonly take equity positions.

Third-Party Finance, where an independent party finances many individual energy systems. This can include hire-purchase, fee-for-service, and leasing schemes, as well as various types of consumer finance.

Consumer Finance, often required for rural clients as a means of making modern energy services affordable. Various types of micro-credit schemes are now being deployed in the solar home system market, for example, that often involve risk-sharing at the local and institutional levels. Once client creditworthiness is proven, the portfolio can be considered an asset and used as collateral for financing.

From an economic perspective, there is no reason why the capital requirements of the industry cannot be met.³⁰

The availability of capital in many developing countries, however, is limited by the high costs and perceived challenges of doing business there, including political risk, project risk, and unfriendly policy frameworks. Together, these issues create a “cost of capital” (the cost of money) that is often much higher than in developed countries.

The cost of capital is particularly a problem for RET projects considered to have a high risk. In addition to the high cost of capital, traditional forms of corporate finance are sometimes inappropriate for more entrepreneurial ventures (see sidebar on this page). To overcome these hurdles, several innovative financing mechanisms for RET developers and end-users have

been devised and tested by international organisations, governments and NGOs (see the appendix for a brief description of some of these organisations).

International public sector financial institutions, including the World Bank, are moving rapidly from the traditional government and subsidy-centered approach, to a financing approach that promotes RETs through energy markets, and where consumer financing or fee-based services are the most important financing models.

The most common *dealer model* creates cash sales by RET equipment dealers. For example, more than 100,000 Kenyan households use PV systems sold through existing rural sales points, such as general stores. The average monthly payment for a solar system is generally less than the monthly cost of kerosene or battery-charging.

The *concession model* depends on regulation, and is geared to provide large economies-of-scale where concessionaires are given franchise rights. These rights are based on bids that require the lowest subsidy to service rural households and community centres. The choice of an appropriate, cost-effective, off-grid technology rests with the concessionaires. Bank financing provides partial financing of start-up costs, while payment for energy services is made by consumers. This model can help achieve economies-of-scale from mass production by increasing market size. The Argentinean PAEPRA programme aims to supply electricity to 1.4 million rural residents and more than 6,000 public facilities through private rural energy-service concessions.³¹



Small amounts of electricity can often make a large difference. (Photo: Jim Welch, courtesy NREL)

In the *retailer model*, a community, organisation, or entrepreneur is given a loan, based on a business plan, to serve a local demand for electricity. The cost of the loan is recovered through a fee-based service arranged with the community and/or consumers. Currently used in Sri Lanka and Laos, the model encourages significant local involvement.

Green Power

In developed economies, a growing source of funds for RET investment is through a “green power” marketing instrument. Using this method, a utility agrees to provide a portion of a customer’s electricity from a renewable source, and the customer agrees to pay a premium for the clean energy. This new electricity “product” has resulted, in part, from the forces of competition that are compelling electricity utilities to differentiate themselves in a very competitive market. Green power programmes have led to new capacity and declining costs for renewable energy with the result that, in some electric utilities today, there is often little or no premium charged for green power.

The City of Oakland, California (USA) aims to become the world's largest municipal purchaser of renewable energy, with plans to purchase 100 percent of the electricity it uses from RETs. The city will pay a premium of \$70,000 over its current \$4 million annual power bill for its “green electrons.”

Surveys show that many customers are willing to pay more for clean electricity. However, current barriers prevent RETs from competing fairly in the marketplace, and inhibit the development of “green markets.” Consequently, although pilot programmes have shown promising results, participation levels to date are around one to three percent of customers. The most optimistic green marketers expect that 20 percent of residential customers, and 10 percent of commercial customers, will choose green suppliers within five years of being given the choice to do so.

Green power products currently on offer have been successful so far because consumers are becoming increasingly aware of the environmental impacts of energy use, and are reassured by

the independent verification that the “green power” they have purchased has actually been generated.

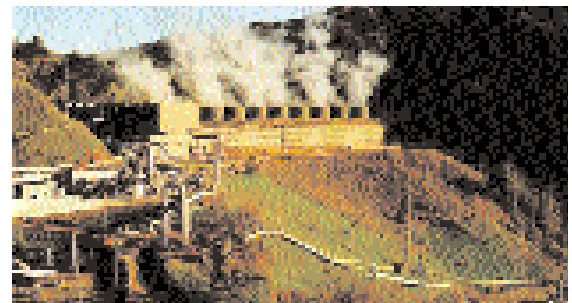
Importance of RETs for Sustainable Development

Twenty percent of the world’s population uses 60 percent of the world’s energy, produces 80 percent of world’s GNP, and enjoys a high material standard of living provided in part by relatively cheap energy. At the same time, more than half the world’s men, women, and children—some 2.8 *billion* people—live in rural areas of developing countries without access to modern energy services.

For the vast majority of these people, energy choices are extremely limited. The rural poor in particular depend on traditional fuels such as wood, dung, and crop residues, usually burned in appliances that are inefficient. For many families, this energy barely meets basic cooking, heating and lighting requirements, let alone the needs of income-generating activities.

Twenty percent of the world's population uses 60 percent of the world's energy to produce 80 percent of the world's GNP.

The harsh reality is that this dependence on traditional fuels requires long hours of collecting materials, puts pressure on the environment, and produces levels of indoor air pollution that exceed outside air pollution in the world’s most polluted cities. Each year, an estimated 500,000 women and children under five years of age in developing countries die prematurely from causes that may be attributable to household solid fuel use.



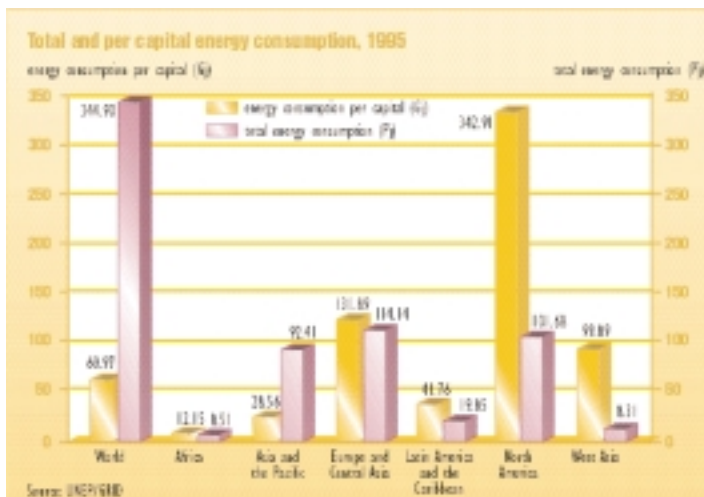
Geothermal power plants are part of new green power marketing programs. (Photo: Pacific Gas and Electric, courtesy NREL)

The key to supplying energy services to people in developing countries lies in a shift of thinking away from large, centralised power grids towards smaller, decentralised systems—particularly systems based on renewable energy technologies.

There is, then, a clear link between *energy poverty*, hunger, and ill health. Yet, the United Nations Food and Agriculture Organisation and the World Energy Council estimate energy roughly equivalent to just seven percent of the world's current electricity production could meet the basic human needs of all rural people in developing countries.

Although many energy tasks do not require electricity, it is considered an essential aspect of social and economic development. Just small amounts of light available at night, for example, can greatly assist education, while electricity makes communication and refrigeration possible. In developed countries around half of the energy used is for heat, 30 percent for transport, and 20 percent for electricity for lighting and other uses.

The number of rural households with access to electricity doubled in the period from 1970–1990, but this expansion has barely kept pace with population increase. Excluding China (where significant progress has been made with rural electrification), only 33 percent of the rural population in developing countries has access to electricity at the beginning of the 21st century. This is the same percentage as 20 years ago.



This means that more than two billion people have no access to electricity, including nine out ten Africans. At least another half billion people have such limited or unreliable access that, effectively, they do not have access at all. Making decisions that first support environmental principles is a luxury that many decision-makers in developing countries believe they cannot afford.



The modular nature of RETs, such as this 50 kW PV array, means the system can grow as power is needed. (Photo: Roger Taylor, courtesy NREL)

The reasons to provide energy services with lower environmental impacts must therefore be based on providing opportunities that satisfy urgent development needs in a sustainable way.

Growing and developing the economies of nations with new and clean renewable energy technologies can provide direct benefits, such as much needed energy services in domestic, transport, and industrial sectors, as well as indirect benefits such as improvements in public health. Furthermore, RETs offer an excellent opportunity to “leapfrog” the heavily polluting energy path of developed countries.

In the same way that new high-tech companies in developing countries can now skip making bulky computers with electronic tubes and start off making PCs with integrated circuits, developing nations can also avoid the environmental pitfalls of fossil fuel development and start fresh with the cleanest options. This must be done carefully, but there are usually many opportunities for innovation when a country is not committed to previous solutions by its past development.

In many developing countries, for example, a wireless cellular phone network is the easiest and least expensive means of providing *communication*

services. Likewise, a wireless electricity system based on RETs and energy-efficient end-use equipment may be the most effective solution to providing new and desperately needed *energy* services.

Historically, there has been a strong correlation between growth of GDP and use of energy. This increasing *energy growth* is often cited as a necessary path to—and result of—economic development. Although this was certainly true in the past, new technologies that improve energy efficiency in both energy supply and use mean that we can now achieve a significantly lower *energy intensity* to attain the same level of energy services. In the US, for example, the amount of energy needed to produce one dollar of GDP fell 42 percent between 1970 and 1999.³²

Consequently, rapidly industrialising countries can choose the best energy-efficient technologies available today to create a standard of living as high as Western Europe in the 1970s, using only a fraction of the energy previously needed to attain that standard. This dramatic improvement for billions of people would represent a mere 10 percent increase in current energy use.³³

There is ample evidence that economic growth can be “decoupled” from increasing carbon emissions.

The link between *carbon intensity* and development needs to be broken. There is ample evidence that economic growth can be “decoupled” from increasing carbon emissions. From 1997–1999, for example, global carbon emissions from the combustion of fossil fuels remained the same, while the world’s economy grew by 6.8 percent. This resulted in a 6.4 percent decrease in the carbon intensity of producing \$1,000 of income. In China, the world’s second largest emitter of carbon dioxide, the economy grew by 7.2 percent in 1998 while emissions dropped by 3.7 percent.³⁴ In the US, carbon intensity fell by 47 percent in the period 1970–1999.³⁵



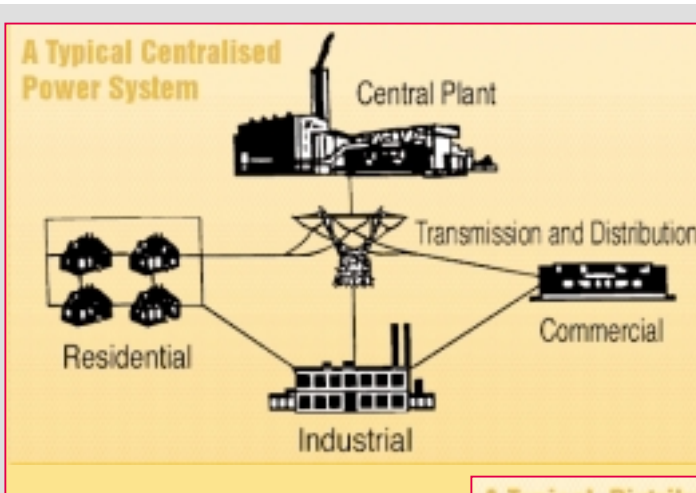
PV can provide essential electricity for water pumping. (Photo: Harin Ullal, courtesy NREL)

Despite much effort, however, little progress has been made to bring clean energy to developing countries, and new approaches are needed. Rural development in general, and rural energy specifically, need to be given higher priority by policy-makers. RETs must be assured a fair opportunity to compete with other energy resources to deliver energy services.

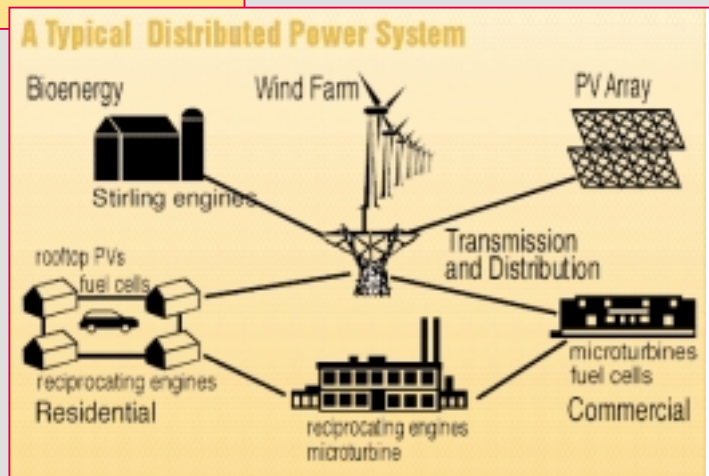
Rural energy development will proceed more rapidly if energy systems are decentralised, and if management of local resources is the responsibility of rural people. If rural energy development is integrated with other aspects of rural development, the process of overcoming the institutional barriers between agriculture, infrastructure, and education, as well as social and political obstacles, will be easier. In some places, this integration and decentralisation has been achieved, but not by massive government investments. Instead, a revolution in finding ways to meet the challenge has created new markets mechanisms, patterns of ownership, and institutional environments.

Technically, many developing countries have an advantage when using RETs based on solar power. In these countries, the amount of solar energy collected can be two or three times higher than in the

northern regions of industrialised countries, and have much lower seasonal swings. For these reasons, developing countries may enjoy a five-to-one cost advantage using direct solar technologies.



The Changing Nature of Electricity Generation and Distribution



Source : Worldwatch Institute

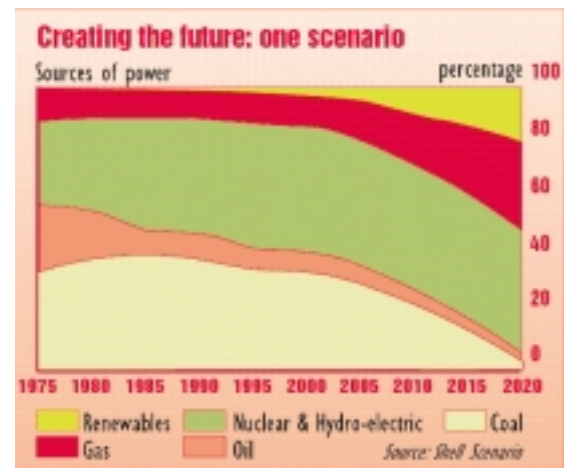
There is a path to a future where substantial economic development is achieved while the damaging environmental impacts of energy use are simultaneously reduced. This path can also lead to a *better* economic outcome than a path that continues to couple energy growth to economic development. This path, however, will be very much “business unusual.”

It is often cited that the cost of switching to low-carbon alternatives, such as renewable energy, is too high. However, the majority of studies have put the cost of this switch in the range of one to six percent of the world’s current GNP, which would pay for a 50–60 percent abatement of emissions by the middle of this century. Using the high end of this estimate, the switch would mean that less than two year’s growth of world GNP would be lost over a 50-year period. This switch would shave less than 0.1 percentage points per year off long-term growth rates, which are currently two percent per year in developed countries and over four percent in developing countries with progressive economic policies.³⁶ It is particularly important to remember that this analysis of costs does not reflect the additional *benefits* that the switch to lower carbon alternatives would bring, such as health benefits from better air quality.

Literally hundreds of future scenarios have been developed by both private and public institutions, using numerous computer-modeling tools. Scenarios by the Intergovernmental Panel on Climate Change, the World Business Council for Sustainable Development, the World Energy Council, the Union of Concerned Scientists, and companies such as Shell, have all explored the necessary policy instruments needed to create a sustainable energy future.

The change needed to realise a “sustainable” scenario is indeed challenging, and requires global technical innovation through strong R&D, enlightened corporate action, progressive government policy, and empowered local groups. Most importantly, these scenarios assume that resources are more equitably shared.

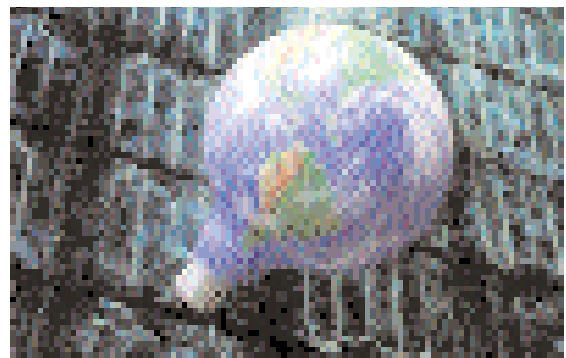
A key point to remember is that the diffusion of new energy technologies has historically been a slow process, ranging from a decade or two to more than a century. The diesel engine, for example, took about 60 years to become a fully accepted and commercial technology. Therefore, a principle conclusion of many sustainable



energy scenarios is that the long-term future, and the transition to new energy technologies, will largely be determined by the technical choices made in the *next few decades*. If certain decisions are not made today—in R&D investment for example—then some future paths will become “locked in” and others “locked out.”

The most common thread among most sustainable energy scenarios is that they are *not* achievable with current policies and prevailing development trends. Their achievement often requires fundamental change and dictates a global perspective, a long time horizon, and immediate policy measures, because of the long lead times needed for change inherent in the energy system.

In a world where the political cycle can be as short as two years, but where a technology cycle may be 50 years or more, the challenge is daunting. As the inventor of the high efficiency compact fluorescent light bulb, Arthur Rosenfeld, testified to a US Senate subcommittee on the nation’s energy policy: “We have a twenty-year goal, divided into five-year plans, administered by two-year elected officials under uncertain one-year budgets.” To reach a goal in this context will require much more than technical innovation.



(Photo: Jerry Downs, courtesy NREL)

Multilateral and Regional Programmes Related to RETs

United Nations Environment Programme (UNEP) www.unep.org/energy

UNEP's Energy Programme addresses the environmental consequences of energy production and use, such as global climate change and local air pollution.

UNEP Collaborating Centre on Energy and Environment (UCCEE) www.uccee.org

UCCEE is a UNEP collaborating centre specialising in energy and environmental issues.

UNDP Energy and Atmosphere Programme (EAP) www.undp.org/seed/eap

The EAP is the focus for UNDP supported activities in the field of energy, linking energy and environment, energy and socio-economic development, as well as looking at how energy and atmospheric pollution issues relate.

UNIDO Energy and Environment www.unido.org/doc/online.htmls

This page provides temporary access to the previously-established UNIDO sites dealing with energy and environmental issues and sustainable industrial development.

UNDP/Global Environment Facility Small Grants Programme www.undp.org/gef/sgp/main.htm

The GEF Small Grants Programme provides grants of up to \$50,000 and other support to community-based groups and non-governmental organisations for activities that address local problems related to the GEF areas of concern.

World Bank Climate Change programmes www-esd.worldbank.org/cc

This page provides links to the World Bank's programmes that are related to climate change.

Energy Sector Management Assistance Programme www.worldbank.org/html/fpd/esmap

A World Bank/UNDP bilateral-donors programme which links various energy, environment, and development issues.

World Bank Asia Alternative Energy Group (formerly ASTAE) www.worldbank.org/astae

A programme promoting renewable energy and energy efficiency in Asia through the bank's power sector lending operations.

World Bank Regional Program on Traditional Energy Sources (RPTES)

This bilaterally funded program studies the functioning of traditional energy markets in the African region.

Activities Implemented Jointly (AIJ) www-esd.worldbank.org/aij

This World Bank programme demonstrates the potential for Joint Implementation to reduce greenhouse gas emissions.

International Energy Agency (IEA) www.iea.org

The IEA is an energy forum that is committed to take joint measures to meet oil supply emergencies, share energy information, co-ordinate energy policies, and co-operate in the development of rational energy programmes.

UN Framework Convention on Climate Change (UNFCCC) www.unfccc.de

This is the convention signed in Rio de Janeiro in 1992 that forms the framework for international efforts to address global warming and climate change.

Intergovernmental Panel on Climate Change (IPCC) www.ipcc.ch

The IPCC is a joint UNEP/World Meteorological Organisation panel assessing scientific, technical, and socio-economic information relevant to climate change.

Multilateral funds focused on the financing and commercialisation of RETs

Global Environment Facility (GEF) www.gefweb.org

The GEF is the international fund created under the auspices of the UN Framework Convention on Climate Change to assist developing and economies-in-transition countries in preparing for, and mitigating, climate change. It is implemented jointly by the World Bank, UNDP, and UNEP.

Prototype Carbon Fund (PCF) www.prototypecarbonfund.org

Launched by the World Bank in 1999, this fund buys carbon emission reduction units from projects likely to qualify under one of the Kyoto emission mechanisms.

Renewable Energy and Energy Efficiency Fund (REEF) www.ifc.org/pressroom/Archive/2000/00_97/00_97.html

This International Financing Corporation (IFC) fund invests in private sector renewable energy and energy efficiency projects in developing countries.

Photovoltaic Market Transformation Initiative (PVMTI) www.pvmti.com

This IFC fund is focused on accelerating the growth of PV markets in India, Kenya, and Morocco by providing financing to private sector enterprises on near-commercial terms.

Small and Medium Scale Enterprise Program (SME) www.worldbank.org/ifc/enviro/EPU/SME/sme.htm

An IFC activity supported by GEF to finance biodiversity and climate change projects carried out by small- and medium-scale enterprises in GEF-eligible countries.

African Rural Energy Enterprise Development (AREED) www.areed.org

A UN Foundation financed initiative managed by UNEP which supports sustainable energy SMEs in five West and Southern African countries.

Solar Development Group (SDG) www.worldbank.org/ifc/enviro/EPU/Renewable/Photovoltaics/SDG/sdg.htm

Conceived as a free-standing, commercial enterprise by the IFC, the SDG's primary objective is the development of viable, private sector business activity in the distribution, retail, and financing of off-grid PV applications in developing countries.

Public, private, and non-governmental organisations financing RETs in developing countries

E&Co www.energyhouse.com

This non-profit energy investment service provides small loans, technical assistance, intermediary services, finance, and direct investment to renewable energy companies.

Environmental Enterprises Assistance Fund (EEAF) www.eeaf.org

EEAF is a non-profit organisation that operates as a venture capital fund, providing long-term risk capital to environmental businesses in developing countries.

India Renewable Energy Development Agency Ltd. www.solstice.crest.org/renewables/ireda

IREDA is a public financial institution promoting and financing investments in renewable energy and energy efficiency projects and companies.

Triodos Bank www.triodos.com

Through its Solar Investment Fund, this Dutch bank finances PV projects in developing countries. Triodos also operates a Wind Fund in the UK, and is fund manager for the Solar Development Group.

Clean Energy Fund www.cleanenergyfund.org

A fund that provides project finance for renewable energy projects.

SolarBank TM www.solarbank.com

SolarBank is a private institution that acts as a secondary lender to existing local primary financial institutions such as banks, co-operatives, credit unions, electric utilities, energy service companies, micro-enterprise lenders, and others who are in a position to finance local PV markets.

RET INFORMATION SOURCES

Developing countries

Governmental and University-based

Blair Research Institute (Zimbabwe) www.healthnet.org/afronets/blair.htm

Energy and Development Research Center, University of Cape Town (South Africa) www.edrc.uct.ac.za

South African Council for Scientific and Industrial Research www.csir.co.za

Regional

Sustainable Markets for Sustainable Energy, Inter-American Development Bank www.iad.org/sds

Non-governmental

ADESOL (Solar Energy Development Association, Dominican Republic) www.rds.org/hn/docs/membresia/directorio/per-ong/adesol.htm

African Center for Technology Studies (Kenya) www.acts.or.ke

Bariloche Foundation (Argentina) www.bariloche.com.ar/fb

Center for Appropriate Rural Technologies (India) www.oneworld.org/cart

Centre for Science and Environment (India) www.cseindia.org

Chinese Academy of Sciences, Energy Division, (China) www.newenergy.org.cn

Green Africa Network (Kenya) <http://members.spree.com/greenafrica>

International Energy Initiative (India) www.climatenetwork.org/candir/candir54.html

International Institute for Energy Conservation (Thailand) www.cerf.org/iiec/offices/asia.htm

Korea Energy Economics Institute www.keei.re.kr/eng-html

Nimbkar Agricultural Research Institute (India) <http://nariphaltan.virtualave.net>

Tata Energy Research Institute (India) www.teriin.org

US-Mexico Foundation for Science www.fumec.org.mx

Industrialized countries

Governmental

Distributed Power Program, US Department of Energy www.eren.doe.gov/distributedpower

International Development Research Center (Canada) www.idrc.ca

National Renewable Energy Laboratory (US) www.nrel.gov

Non-governmental

David Suzuki Foundation (Canada) www.davidsuzuki.org

Distributed Power Coalition of America www.dpc.org

E Source (US) www.esource.com

Electric Power Research Institute (US) www.epri.com

Enersol (US) www.enersol.org

Intermediate Technology Development Group (UK) www.itdg.org.pe

RAND Corporation (US) www.rand.org

Renewable Energy Policy Project (US) www.repp.org

Rocky Mountain Institute (US) www.rmi.org

Royal Institute of International Affairs (UK) www.riia.org

Solar Electric Light Fund (US) www.self.org

Solar Energy International (US) www.solarenergy.org

Stockholm Environment Institute (Sweden) www.sei.org

Worldwatch Institute (US) www.worldwatch.org

Finance

Sarasin New Energies Invest AG www.sarasin.ch/e/r07.html

Gerling Sustainable Development Project www.gerling.com

SAM Group Sustainable Private Equity Fund www.sam-group.com

Triodos www.triodos.com

Vtz www.vtz.ch

Black Emerald Group www.blackemerald.com

Nth Power Technologies www.nthfund.com

Renewable Energy Technology Associations

Geothermal

GeothermalResources Council www.geothermal.org

International Geothermal Association www.demon.co.uk/geosci/igahome.html

International Ground Source Heat Pump Association www.igshpa.okstate.edu

Biomass

Biomass Energy Research Association www.bera1.org

Biomass Resource Information Clearinghouse <http://rredc.nrel.gov/biomass>

Biofuels for Sustainable Transportation www.biofuels.nrel.gov/biofuels.html

Hydro-Power

National Hydropower Association (US) www.hydro.org

International Network on Small Hydro Power www.digiserve.com/inshp

Solar

The International Solar Energy Society www.ises.org

Solar Energy Industries Association www.seia.org/main.htm

American Solar Energy Society www.ases.org/index.html

Windpower

American Wind Energy Association www.awea.org

The European Wind Energy Association www.ewea.org

Fuel Cells

World Fuel Cell Council www.fuelcellworld.org

California Fuel Cell Partnership www.drivingthefuture.org

Notes

- ¹ Unless otherwise noted, all monetary amounts are in US dollars.
- ² World Bank. *Fuel for Thought: An Environmental Strategy for the Energy Sector*. World Bank Publications, 2000. ISBN: 0-8213-4559-0.
- ³ The main greenhouse gases are: carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFC), perfluorocarbons (PFC), and sulfurhexafluoride (SF₆). Information on greenhouse gases may be obtained from the US EPA website on climate change at www.epa.gov/ghginfo/topic1.htm (as of September 2000).
- ⁴ Satellite measurements show that the Arctic ice pack has been shrinking by about three percent per decade since 1978.
- ⁵ Most of this renewable electricity is provided by hydroelectric projects.
- ⁶ Dunn, S., *Micropower: The Next Electrical Era*, Worldwatch Paper 151. Worldwatch Institute, 2000. ISBN 1-878071-53-x.
- ⁷ In many countries, the underlying reasons behind renewable energy promotion may be mixed and encompass energy, environmental, and other objectives. This can complicate the evaluation of such policies, as the costs associated with increased renewable energy use (often borne by public energy budgets) bring benefits in energy and non-energy sectors. For example, increasing farmers' incomes via subsidies for biofuels may help to maintain a country's food production capability, increase regional development, maintain rural employment levels, and reduce emissions of CO₂ as well as increasing renewable energy use.
- ⁸ One megawatt (MW) equals 1,000 kilowatts (kW), the power needed to power about 1,000 standard US homes or about 10,000 highly efficient homes.
- ⁹ Renner, M., *Working for the Environment: A Growing Source of Jobs*. Worldwatch Paper 152. Worldwatch Institute, 2000. The projection of 1.8 million jobs is based on a continued year 1999 industry growth rate of 30 percent per annum. Also, in a 1991 study by Nick Lenssen of the Worldwatch Institute, generating 1,000 gigawatt-hours of electricity per year in the US required 100 workers in a nuclear power plant and 116 in a coal-fired plant, but 248 in a solar thermal facility and 542 on a windfarm.
- ¹⁰ Renner, op. cit. note 8.
- ¹¹ Mellecker, D., *Solar Energy: Local Manufacturing and Sustainable Development*, Sustainable Development International, www.sustdev.org/explore/energy/index.shtml (viewed September 2000).
- ¹² In some countries, import and custom fees may increase these costs.
- ¹³ UN Development Programme, UN Department of Economic and Social Affairs, World Energy Council, *World Energy Assessment*, UNDP Publications, 2000. ISBN: 92-1-126126-0.
- ¹⁴ Mixed solid municipal waste contains items such as plastics that can be burned to generate heat, but these plastics are derived from fossil fuels. Municipal waste also includes glass, metals, and ceramics that cannot be combusted. Therefore, mixed municipal waste is not technically a biofuel. Hazardous waste regulations may also prohibit burning municipal solid waste.
- ¹⁵ *World Energy Assessment*, op. cit. note 13.
- ¹⁶ Mellecker, op. cit. note 11.
- ¹⁷ Eggerston, B. *Trends in Renewable Energies Newsletter*, Issue 147, September 11, 2000. www.solaraccess.com (viewed September 2000).
- ¹⁸ Ruijgrok, E and Oosterhuis, F., *Energy Subsidies in Western Europe*, paper commissioned by Greenpeace International. Institute for Environmental Studies, Vrije Universiteit, Amsterdam, 1997.
- ¹⁹ Wohlgemuth, N. and Painuly, J., *Promoting Private Sector Financing of Commercial Investments in Renewable Energy Technologies*, paper presented at the United Nations Fifth Expert Group Meeting on Financial Issues of Agenda 21, Nairobi, Kenya, 1–4 December, 1999. UNEP Collaborating Centre on Energy and Environment, Risø National Laboratory, Denmark.
- ²⁰ OECD/IEA. *Enhancing the Market Deployment of Energy Technology: A Survey of Eight Technologies*, OECD Publications, 1999. ISBN: 92-64-15425-6.
- ²¹ Pearce, D. with von Fickenstein, D., *Advancing Subsidy Reforms: Towards a Visible Policy Package*, paper presented at the United Nations Fifth Expert Group Meeting on Financial Issues of Agenda 21, Nairobi, Kenya, 1–4 December, 1999. Centre for Social and Economic Research on Global Environment, University College, London.
- ²² Flavin, C., *World Carbon Emissions Fall*, Worldwatch News Brief, July 27, 1999 at www.worldwatch.org/alerts/990727.html (viewed September 2000).
- ²³ For example, the landlord may choose an energy system for a building that is the cheapest to buy, but not to run. The tenant will therefore have to pay more than if the more expensive efficient system was installed.
- ²⁴ European Commission/UNDP, *Energy as a Tool for Sustainable Development for African, Caribbean and Pacific Countries*. United Nations Publications, 1999. ISBN: 92-1-126-122-8.
- ²⁵ Wohlgemuth and Painuly, op. cit. note 19.
- ²⁶ *World Energy Assessment*, op. cit. note 13, quoting Williams and Terzian, 1993.
- ²⁷ Ruijgrok and Oosterhuis, op. cit. note 17. The figure is for the period 1990–1995.
- ²⁸ *World Energy Assessment*, op. cit. note 13.
- ²⁹ *World Energy Assessment*, op. cit. note 13, quoting World Energy Council 1997.
- ³⁰ *World Energy Assessment*, op. cit. note 13.
- ³¹ In this programme, the government sets tariffs for different types of electricity services. A competitive tender is held, under which companies bid for a 15-year monopoly concession contract. Under the contract, the concessionaire is obligated to service all household and public facilities for which they receive government subsidies. Companies compete partly on the basis of how little a subsidy they are willing to accept.
- ³² Geller, H and Kubo, T., *National and State Energy Use and Carbon Emission Trends*, Report Number E001. American Council for an Energy-Efficient Economy, 2000.
- ³³ *World Energy Assessment*, op. cit. note 13, sec 2.2.
- ³⁴ Flavin, op. cit. note 22.
- ³⁵ Geller and Kubo, op. cit. note 32.
- ³⁶ *World Energy Assessment*, op. cit. note 13.

