Wind Power Versus Plutonium:

An Examination of Wind Energy Potential and a Comparison of Offshore Wind Energy to Plutonium Use in Japan

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Foreword

This report is part of IEER's global outreach program on reducing nuclear dangers, and on achieving complete and enduring nuclear disarmament. The energy choices we make will likely shape the environment of the Earth for generations to come. They will also profoundly affect the prospects of reducing proliferation risks, and of achieving stable and enduring nuclear disarmament. No energy-related question is more pressing and more important for non-proliferation and disarmament purposes than the future of plutonium use in the commercial economy.

For over half a century, the nuclear establishment has promised the world energy from plutonium. It was to be plentiful in supply, lasting into the indefinite future and, in the 1950s, even "too cheap to meter." After tens of billions of dollars in research and development expenditures and little to show for it, programs for the use of plutonium must be viewed as failures.

Plutonium is now widely recognized as an uneconomic fuel. It is not even competitive with uranium and is unlikely to be in the foreseeable future. However, its proponents point out, as they have done from the start of the nuclear power era, that once-through uranium fueled reactors use a very small portion of the uranium resource base because they rely mainly on uranium-235, which is only 0.7 percent of natural uranium. The most abundant isotope, uranium-238, which is almost 99.3 percent of natural uranium is almost completely wasted (though a small portion is converted to plutonium and fissioned in the course of reactor operation). Since economically extractable uranium resources are unlikely to be a fuel source for the millennia to come, the advocates of plutonium point out that the conversion of uranium-238 to fissile plutonium fuel in breeder reactors is necessary for a long-term nuclear future.[1]

The key technology, the breeder reactor, converts uranium-238 (which is not a nuclear reactor fuel) into plutonium (which is). However, breeder reactors have a dismal record, especially given the amounts of resources that have been poured into them. Of the 2,600 megawatts of breeder reactor capacity in the mid-1990s, almost half was in a single reactor in France, Superphénix, which has since been shut. Moreover, the technology needed to separate plutonium from irradiated reactor fuel is in many ways the dirtiest part of the nuclear fuel cycle. It has been responsible for extensive pollution of the seas, rivers, and soil. It has resulted in highly radioactive liquid waste, which must be stored in

[1] The argument for the conversion of non-fissile thorium-232 into fissile uranium-233 is about the same as that for converting uranium-238 into plutonium, with the difference that the practical utilization of thorium-232 has faced even greater obstacles than plutonium.

tanks. Among the problems posed by these tanks is the risk of catastrophic explosions, such as that which occurred in a military high-level waste tank in the Soviet Union in 1957, and there was an electrical power failure at the French reprocessing plant at La Hague in 1980 that could have resulted in disaster but fortunately did not. Moreover, plutonium fuel use puts weapons-usable plutonium into circulation in the commercial economy, increasing proliferation dangers.

Plutonium is not the only fuel that can provide energy for the indefinite future. Wind and solar energy are two obvious alternatives to it. Even advocates of nuclear power admit their environmental and security advantages. However, advocates of nuclear energy have long argued that these are not economical. This is a specious and misleading argument on several counts. Plutonium is not economical – in fact, costs have gone up over time. Moreover, improvements in technology have made wind energy economical in some circumstances already. In addition, breeder reactors are not even a sound energy strategy for energy independence, as our analysis shows.

The relevant question for the long-term energy future is not whether wind, solar, or plutonium are economical now, but how we can arrive at an energy future that is environmentally sound, economically viable, and addresses the problems of greenhouse gas build-up and proliferation concerns all at the same time. This study does not address the whole complex of the issues involved, but rather one component – is it sensible at all to invest in plutonium as a long-term energy resource given that wind power is commercial in some circumstances and can be made widely commercial in the foreseeable future?

In comparison to plutonium, renewable energy sources have received a far smaller share of public resources for technological development despite the evident superiority on environmental and non-proliferation grounds. Wind power has no routine emissions and no long-lived radioactive wastes, for instance. One result has been that the development of renewable energy sources has been slow and halting. However, the total amount of wind power is still very small both in relation to its potential and as a fraction of total electricity generation. Nonetheless, in the last two decades, significant improvements have been made. In the 1980s, the first major wind farms were built in California, and in the 1990s, wind power developments have been significant in Denmark and Germany. Denmark has made a major difference to the development of wind power technology through its ambitious and long-range commitment to it. The industry is evolving and improving rapidly, especially since the early 1990s. One of the major constraints on wind power development, the large amount of land required, is now being loosened by the development of offshore wind power plants. Sweden, Denmark, and Holland have been trying them out since 1990, with good results. Again, Denmark has the best-developed plans for expansion.

Our case study was on plutonium fuel use in nuclear reactors for Japan, which has among the most ambitious plutonium programs in the world. Moreover, the land constraints in Japan are severe and the land-based wind power potential is relatively low.

We decided to compare the costs and electricity generation potential of using plutonium as a fuel with those of offshore wind development in Japan. The basic purpose of the comparison is to explore a long-term energy source for Japan and to discuss a short- and medium-term investment strategy that derives from that analysis. For the long-term analysis we compare the use of breeder reactors with plutonium recovery to wind energy, based on costs that are roughly comparable to those that currently prevail. While the costs of breeder reactor technology and associated reprocessing may decline, this is not at all assured; nor can such a trend be discerned from past development of this technology. On the other hand, there is a clear trend toward lower costs of wind energy. Thus, a comparison based on approximate current costs yields results that are biased against investment in wind. Despite this, our analysis clearly shows the desirability of long-term investment in wind energy.

The short- and medium-term analysis that is needed in such a situation is to compare the benefits that can be derived from the development of wind power compared to plutonium programs over the same period. These involve the use of plutonium fuel as a fuel in current light water reactors, which is the transitional plutonium use strategy that has been adopted by France, Japan, and others.[2] The fuel consists of a mixture of a few percent of plutonium dioxide mixed with uranium dioxide, called MOX fuel. Were the short- and medium-term economic benefits of MOX fuel use relative to wind overwhelmingly great, an economic argument could be made for the development of wind and plutonium technologies in parallel. But this is not the case. MOX fuel carries high costs as well and environmental and proliferation liabilities that are not shared by wind technology.

The results of our research point clearly in the direction of offshore wind energy development for Japan. Based on preliminary survey of the literature on the subject, offshore wind potential could also be similarly developed in many other countries, including those that now have large plutonium programs: Britain, France, and Russia. Of course, due to their large land area, land-based wind energy may be a better choice for Russia and several other countries that were formerly part of the Soviet Union.

In 1952, the Paley Commission, appointed by President Truman, judged the promise of renewable energy sources to be greater than that of nuclear power for meeting energy needs and preventing economic dislocations due to disruptions in foreign oil supply. But shortly thereafter, the US government chose to ignore that recommendation in favor of pursuing nuclear power, largely as part of its Cold War propaganda campaign.[3]

It is well past the time when Cold War dreams of plutonium as a "magical" energy source should have been abandoned in favor of renewable energy sources. I hope that this study

[2] MOX fuel use in light water reactors is not a suitable strategy for using most of the uranium resource base. This is because repeated recycling of plutonium in these reactors degrades the isotopic composition of the plutonium. Isotopically-degraded plutonium eventually becomes unsuitable for use as a fuel.

[3] Paley Commission as cited in Makhijani and Saleska 1996.

will spur Japan as well as other countries to vigorously pursue wind energy. The same level of resources as have been expended on plutonium energy are not likely to be required, since wind energy is already commercial relative to plutonium in many locations. But the same determination will be needed. It will also require some political courage to put aside the pork-barrel claims of the plutonium establishment, which has had an unduly large claim on the public purse for over fifty years and still exercises a high level of bureaucratic influence in several countries.

A word is warranted here about recent developments in Germany. The new German coalition government of the Social Democratic and Green parties has decided to phase out nuclear power. In conjunction with this decision, they will terminate reprocessing as a method of waste management and the use of separated plutonium as a fuel source. Germany's decisions regarding reprocessing may well be the harbinger for a thorough reassessment of the plutonium commitments by other countries. Following on the heels of the German decision, Switzerland, another country that uses MOX fuel, also announced a decision to phase-out nuclear power and use of plutonium for energy. Neither country has settled on a timetable as yet

As a result of the German decision to stop reprocessing, Japan will become by far the largest foreign customer for French and British reprocessing services. A decision by Japan to develop wind energy instead of plutonium could play a big role in convincing the British and French to end their own uneconomical commitment to this fuel.

The rapid developments in favor of wind energy and against plutonium as an energy source come at a time of an urgent need for new electrical generating capacity designed to reduce carbon dioxide emissions. Our analysis shows that one essential component of investment in long-term energy sources should be wind energy and specifically development of offshore wind resources. It is time to leave plutonium behind in the century in which it was created and stop throwing good money after the enormous amount of public resources have already been wasted on it.

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Summary of Findings and Recommendations

The energy carried by the wind holds immense potential to contribute to the world's electricity supply. Many factors have held back the realization of that promise. The relative lack of resources for its development compared to fossil fuels and nuclear energy (especially plutonium programs) has been a major factor. But the amount of land required and the dispersed and intermittent nature of the resource have also constrained its development.

Internal technical constraints on wind energy development now appear to have been largely resolved or nearly so. In the last two decades developments in electronics as well as increasing wind turbine size have reduced the costs of connecting turbines to electricity grids. As a result, the economics and reliability of wind turbines has been greatly improved. Further, the location of wind turbines in offshore areas since 1990 appears to be a solution for coastal countries where wind energy development is limited by availability of land.

As a result of the removal of these major constraints on wind energy development, wind energy should now be regarded as a major energy source. The reduction of greenhouse gases and increasing self-reliance in energy supply have been posited as attractive characteristics of both plutonium and wind energy programs (though not perhaps by the same authorities). Both plutonium and wind have been suggested as energy sources for the indefinite future (in contrast to fossil fuels or uranium-235). Hence a comparison between them is appropriate. One difference between wind energy and plutonium as a fuel (or other nuclear or fossil fuels) is that wind is by its nature intermittent. Hence, wind power sources must either form part of a mix of electricity, or, if wind is to play a role more akin to baseload generating sources, means such as energy storage or conversion to hydrogen are required.

We have used the Japanese situation as a case study in order to make such a comparison. One reason we chose Japan is that its particular circumstances make it more unfavorable for wind than other countries that have plutonium programs. Japan has very limited availability of land suited for wind power, and much of it is expensive to access. Hence, Japan provides a suitable case to test the viability of wind power versus plutonium, in order for our findings to be generally applicable to other countries with plutonium programs.

Main Findings

1. The global wind energy resource is very large and can make significant contributions to the world's electricity supply. Both land-based and offshore wind energy resources are substantial.

Overall, wind energy can supply a significant fraction of the world's electricity supply. Land-based wind energy supply greatly exceeds current total world electricity generation. Only a fraction of this can be economically tapped with present technology at suitable locations. Global offshore wind potential has not been well studied, but European estimates indicate that it is also large.

2. Offshore wind power holds great promise and can overcome the principal objections to land-based wind power.

The size of this resource will depend greatly on technology, since current technology limits economic exploitation to relatively shallow waters. Siting wind power plants offshore eliminates land impacts, and visual impacts could be greatly reduced or eliminated. The potential of offshore wind energy has not been carefully evaluated except in parts of Europe, but it is likely to be significant. The increased cost of offshore construction and connection to land-based transmission lines are likely to be offset to a large degree by more favorable winds, lower site acquisition costs, and reduced environmental impacts. Offshore costs are projected to be roughly the same as moderately-good land-based sites – about 5 cents per kilowatt-hour (kWh). Denmark has embarked on an ambitious wind power development program and much of this expansion will be in the form of offshore wind plant plants.

3. Japan's plutonium program is expensive and uneconomical.

Japan has spent enormous resources trying to develop its plutonium program. The capital cost of the Rokkasho reprocessing plant alone is estimated to be $11 billion by the time construction is completed. Japan has spent many billions more on foreign reprocessing contracts, on the Tokai reprocessing plant, and its breeder reactor program. Yet:

- Not a single commercial reactor in Japan is using plutonium fuel.
- Japan's breeder reactor program is stalled for a variety of reasons, including a December 1995 sodium leak in its showcase breeder reactor project at Monju.
- The full-scale reprocessing plant under construction at Rokkasho is far behind schedule and greatly over budget. Japan’s pilot reprocessing plant at Tokai is shut.

4. Japan has few indigenous fossil or uranium energy resources. Yet Japan has not made a significant effort to develop its wind power resources. Japan has modest land-based wind energy potential and substantial offshore wind potential.

Japan relies on imports for most of its energy use. It is reliant on foreign sources for coal, oil, natural gas, and uranium. Japan derives about 11% of its total primary energy supply (about 28% of its electricity supply) from nuclear power. It has built only 25 MW of wind capacity through mid-1998. Its expenditures on plutonium have been hundreds of times larger than on wind energy development – a difference that cannot be justified based on the experience of these two programs or on the potential of these two resources.

A wind resource survey completed by the New Energy and Industrial Technology Development Organization, NEDO, gave a mid-range estimate of land-based wind power equivalent to 1 to 3 percent of total electricity production. Japan's offshore resources appear to be much greater. A preliminary study estimated the offshore wind energy potential for a range of scenarios 1 to 5 kilometers from the coast to be 9 to 28% of electricity generation in 1996. Wind resources up to 40 kilometers from shore are currently considered economically feasible according to studies in Denmark, with the key factor being water depth. If equivalent areas far from shore can be developed, the Japanese offshore wind resource would be far larger. Yet Japan's energy policy has no provision for the development of its offshore wind potential.

5. A vigorous program to develop wind energy could, by the year 2010, result in annual electricity generation approximately equal to Japan's plans for electricity from mixed oxide fuel program in 2010.

Current Japanese plans call for 17 reactors to be using mixed plutonium oxide-uranium oxide (MOX) fuel by the year 2010. Japan's wind potential, notably its offshore potential, could be developed to almost equal the 39 TWh per year that would be generated from MOX fuel if Japan's plutonium fuel plans stay on schedule. (However, we note that Japan's plutonium program has experienced many setbacks and delays in recent years.)

6. The cost of electricity from plutonium is greater than expected offshore wind energy costs.

Current estimates based partly on European experience since 1991, indicate offshore wind energy costs of under 6 cents per kWh. We estimate electricity generated from MOX fuel in current nuclear reactors to cost 7 to 8 cents per kWh, possibly more. We estimate electricity from breeder reactors to be 11 to 12 cents per kWh, under optimistic assumptions, and they may be as high as 15 cents per kWh. There is no trend indicating decreasing breeder reactor costs. In contrast, wind energy costs will likely continue to decrease, as the demand for wind turbines increases and large-scale production is established.

7. Further expenditures of ratepayer and taxpayer resources on electricity from separated plutonium (including expenditures on reprocessing) are unjustified and represent a gross misallocation of energy development money.

The size of the offshore wind resource, the availability of the technology, the many difficulties with plutonium as an energy source and the high cost of using plutonium all point to same conclusion. A rational energy policy cannot justify continued expenditure on plutonium fuels. Our conclusions in this regard are based on our case study of Japan. However, costs of plutonium programs are broadly similar in various countries and hence our conclusions are also likely to be valid for other countries with potential for offshore wind energy development, such as France, Britain, Russia, and the United States.

8. A hydrogen-based transportation system would be more economical using wind as an energy source rather than breeder reactors.

The use of hydrogen as an energy carrier in the long-term is desirable for a number of technical and environmental reasons. In particular, an energy self-sufficiency strategy in transportation for countries that rely on imported petroleum is likely to involve the use of hydrogen and fuel cells in transportation. To accomplish this, the conversion of electricity generated whether from wind or from plutonium (or nuclear power generally) to hydrogen fuel will be required. On the basis of present costs and projections, hydrogen derived from wind energy is far superior economically as well as environmentally to that derived from plutonium as a fuel.

Recommendations

1. Japan should end its program for generating electricity from separated plutonium, including its MOX program for light water reactors and its breeder reactor program.

2. Japan should immediately begin serious evaluation of offshore wind energy resources and start programs in favorable locations. It should aim to generate enough electricity from wind to replace the projected energy generation from plutonium fuel through the year 2010.

An ambitious offshore wind program is both justifiable and prudent. It will be large enough to provide a solid basis for economic and environmental evaluation and provide sufficient operating experience on which to gauge the true potential of the energy resource.

3. The International Energy Agency and the United Nations Environment Programme, in collaboration with other agencies such as the World Meteorological Organization, and national governments should undertake a comprehensive survey of global offshore wind potential.

More detailed estimates of offshore wind energy potential are needed, calculated based on wind turbines optimized for offshore wind conditions.

4. Government policies should be aimed at creating a predictable and significant market for wind energy, including offshore wind energy, given the need to reduce greenhouse gas emissions.

Our evaluation of past governmental efforts to develop wind energy leads us to conclude that the most effective way to promote wind energy is to hold open bids for a fixed amount of wind capacity each year at appropriate sites, including offshore locations. These bids should require guaranteed performance over a specified period of time, on the order of 15 to 20 years. The competitive nature of this program would reduce the cost of wind electricity. In particular, we recommend that the United States government put in place a program to purchase 1,000 megawatts a year of wind capacity at least until the year 2010. Such a program is justified both in view of the magnitude of U.S. commitments to greenhouse gas reduction under the Kyoto Protocol and the broad economic and political influence that such a policy would have in the private sector as well in other countries. Similar programs should be put in place for other renewable energy technologies; taken together, they would form a substantial part of a comprehensive approach to decreasing the costs and increasing the use of renewable energy.

5. ***Offshore wind energy projects that are undertaken over the next two decades should have significant components that would evaluate their environmental impact on marine ecosystems.***

6. Given that hydrogen is a non-polluting energy carrier that can become part of a sustainable energy system, significant resources should be devoted to the commercialization of this technology, particularly in transportation.

Countries, such as Japan, that claim to have energy self-sufficiency as a priority should incorporate hydrogen into their analyses of energy systems. The use of fuel cells in motor vehicles is being intensively investigated by automobile manufacturers. Efforts by governments to develop hydrogen technology and infrastructure, including use of hydrogen in fuel cell vehicles, would help promote a number of goals simultaneously, including reduction of greenhouse gas emissions and transition to renewable energy sources.

1. Wind Energy Overview

Although people have used wind energy for thousands of years for sailing, pumping water, and milling grain, it took roughly a hundred years into the electric power generation era to see the beginning of the use of wind turbines for electricity generation on a significant scale. As the twentieth century draws to a close, the technology is changing and improving rapidly and costs are coming down. The wind turbines being installed today for production of electricity are highly sophisticated machines that are considerably more advanced than those installed just five or ten years ago.

Through the end of 1997, the estimated global wind electric generating capacity was some 7,636 megawatts (MW).[4] An additional 2,100 MW of wind projects were installed during 1998, an amount exceeding the 1997 record for one year's installation.[5] The annual average increase from 1990 to 1997 was roughly 20%; global capacity doubled between 1994 and 1997.[6]

The U.S. Energy Information Administration estimates that costs of wind electricity have decreased from more than 7 ¢ per kilowatt-hour (kWh) in 1990 to about 4.5 ¢ per kWh in 1996.[7] Costs are expected to continue to decrease in coming years. In some sites, the cost is even lower – for instance, one utility announced a contract for 100 megawatts of wind power at a cost of 3 ¢ per kWh.[8]

Global Wind Energy Resources

Wind energy is a solar resource, created by temperature differences between the sea, land, and air as well as temperature gradients between the equator and the poles of the planet.[9] About 0.25 of the total solar radiation is transformed into wind energy.[10]

Practical limitations to converting this large amount of energy into usable work are evident. About 70% of the Earth's surface is covered by oceans; most of the wind resources there remain too difficult to tap. Most land area is used for other purposes, including protection of ecological systems. Further, the intermittent nature of the wind means that each kilowatt of capacity will generate only one-third to one-half of the

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[4] BTM 1998, page iv. Such estimates of wind power capacity figures usually include only "utility-scale" wind turbines, generally rated 50 – 100 kW and greater. The cited figure is the total "nameplate" rating of the installations.

[5] Worldwatch Institute 1999.

[6] Installed capacity in 1990 was about 2000 MW (Flavin 1996). World installed capacity at the end of 1994 was 3,710 MW (AWEA 1997).

[7] Costs in constant 1995 dollars. EIA 1996, page 55.

[8] Price quoted in Northern States Power 1995. The quoted cost is a levelized cost per kWh, reflecting the average price to be paid by Northern States Power over the 30-year life of the agreement.

[9] Grubb and Meyer in Johansson et al., eds. 1993, page 158.

[10] Power measures the rate of energy flux. One watt of power is 1 joule of energy per second. A typical incandescent light bulb consumes about 60 watts of electricity – that is, 60 joules of electric energy per second. The prefix "tera" means one trillion.

amount of electricity per year compared to a typical base-load central power plant rated at the same amount of power. This makes it difficult to use wind as the only source of energy without expensive energy storage. However, wind power systems can be integrated into grids that also contain other sources of electric power supply, as is currently done. It appears possible to incorporate a significant fraction (25 to 45 percent of system energy seems feasible for most systems[11]) of wind into a large electricity grid without major investments in upgrading transmission and distribution infrastructure or the need for storage.

The global potential of land-based wind energy is still large, even when such limitations are taken into account. A 1993 study (see Table 1) produced a "first-order" and a "second-order" world wind electricity potential. It should be noted that the assumptions used include significant amounts of resources not considered "commercial" today.[12] The "first order" estimates appear to be unrealistic, given barriers such as constraints on land use. The second order estimates should be viewed as a rough estimate of practical upper limits of land-based wind power potential in the long term.

Table 1: Global Land-Based Wind Energy Electric Potential

Region	**First-Order Wind Electric Potential, TWh per year**	**Second-Order Wind Electric Potential, TWh per year**
Africa	106,000	10,600
Australia	30,000	3,000
North America	139,000	14,000
Latin America	54,000	5,400
Western Europe	31,400	4,800
Eastern Europe and former USSR	106,000	10,600
Rest of Asia	32,000	4,900
World	***498,000***	***53,000***

Source: Grubb and Meyer in Johansson, et al. 1993, page 198.
Note: Estimates do not include Greenland, Antarctica, most islands, or offshore wind resources.
The first-order estimate excluded areas such as cities, forests, unreachable mountain areas, etc.
The second-order potential excluded more lands, based on experience and studies in the United States, Denmark, and the Netherlands. The amount of land excluded in the second-order estimate was related to the average population density. For most areas of the Earth, a factor of ten reduction was used to obtain the second-order available land. For western Europe and parts of Asia, a factor of 6.5 reduction was used, based on siting densities for projects in Denmark. These factors exclude a higher percentage of land than assumed for a study of wind energy potential in the United States.

These estimates are based on data of varying quality and are not suited for site specific use. Many areas have had not had sufficient levels of data collection to allow siting of

[11] Grubb and Meyer in Johansson et al., eds. 1993, page 185.
[12] Grubb and Meyer in Johansson et al., eds. 1993, pages 186-199. Assumptions included: class 3 or better winds; hub height = 50 meters above ground; rotor diameter = 50 meters; turbine efficiency = 35%; array and system losses = 25%; average turbine spacing of 10 rotor diameters by 5 rotor diameters.

turbines. Site-specific measurements, such as seasonal variability and wind turbulence, are needed to properly develop wind resources.[13]

Grubb and Meyer's global second-order estimate of 53,000 TWh per year is four times the global electricity production in 1995 of 13,200 TWh.[14] Grubb and Meyer note that the second-order estimates would involve about 1.5 to 3 percent of land area of the different regions. Countries such as the United States, members of the European Union, China, and Russia, are all major emitters of greenhouse gases; all have major wind energy potential.

The estimates made by Grubb and Meyer do not include offshore wind resources. With the exception of some parts of Europe, few detailed studies have been done to estimate offshore wind resources.[15] A 1994 study estimated offshore resources of 11 western European countries to be 596 TWh for water depths 10 meters and less and 3,028 TWh for water depths of 40 meters and less.[16] The larger estimate is greater than the entire electricity production of these countries. An estimate for Japan found that offshore wind energy resources were much higher than practically available on-shore wind energy resources.[17]

Several European countries are installing offshore wind power plants, with Denmark having the most ambitious plans. Denmark has announced a goal of 4,000 MW of offshore wind electric capacity by the year 2030, producing 13.5 TWh of electricity (equivalent to about 35% of the estimated electricity consumption in Denmark in that year).[18] This capacity is to be installed in four offshore areas identified in a study that targeted areas between 7 and 40 kilometers from the coast and up to 11 meters water depth. Offshore wind power is discussed in Section 2 of this report.

Basic Characteristics of the Wind

The power that can theoretically be generated by a wind turbine is dependent on the density of the air, the area encompassed by the rotating turbine blades (referred to as the "swept rotor area"), and the velocity of the wind.[19] The amount of power generated is directly proportional to the area swept by the rotor blades as they turn. Just as a doubling of the diameter of a circle increases the area of the circle by a factor of four, a doubling of the diameter of a wind turbine rotor increases the swept area, and thus the power, by a

[13] Collection of this type of data is needed for what is called "micrositing."
[14] World Bank 1998, page 152.
[15] For example, the *Structural and Economic Optimisation of Bottom-Mounted Offshore Wind Energy Converters* (Kühn et al. 1998) study funded in part by the Joule III program of the European Commission (January 1996 to December 1997) and the two Offshore Wind Energy in Mediterranean and Other European Seas Conferences held in 1994 and in 1997.
[16] Matthies 1994, as cited in Gaudiosi 1996, page 901. Countries included were Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, and United Kingdom.
[17] Nagai, Ushiyama, and Ueno 1997. See Section 3 of this report for details on Japan's wind resources.
[18] DWTMA 1998, "The Future of Offshore Wind Energy."
[19] One of the best resources for a discussion of the basics of wind energy and technology is the Danish Wind Turbine Manufacturers Association web page, www.windpower.dk.

factor of four. Power increases very rapidly with increasing wind speed – the power increases as the cube of the wind speed. That is, power goes up eight times for every doubling of the wind speed.[20] For example, the power of a 14 meters per second (m/s) wind is 1,681 watts per square meter (W/m^2). This is eight times the power of a 7 m/s wind, which is 210 W/m^2. Table 2 shows the relationship between wind speed and power per square meter of swept rotor area.

Table 2: Calculation of Wind Power Density from Wind Velocity

Velocity (m/s)	Power (W/m^2)	Velocity (m/s)	Power (W/m^2)	Velocity (m/s)	Power (W/m^2)
1	0.6	9	447	17	3,009
2	4.9	10	613	18	3,572
3	17	11	815	19	4,201
4	39	12	1,058	20	4,900
5	77	13	1,346	21	5,672
6	132	14	1,681	22	6,522
7	210	15	2,067	23	7,452
8	314	16	2,509	24	8,467

Note: Air density of 1.225 kilograms per cubic meter assumed (dry air at standard atmospheric pressure at sea level at 15° C)

The dependence of power on the cube of the wind speed is a central consideration in development of wind resource areas. Since power output varies so dramatically with the wind speed, it is crucial to know the distribution of the wind speed in order to evaluate a particular site, and not just the average wind speed. This concept is illustrated in Table 3. All three sites in Table 3 have the same annual average wind speed, yet the annual average wind power is different because the wind speed distribution is different. The locations with higher annual average wind power have more high wind conditions, though for shorter periods of time. This results in greater annual average power than that from a more evenly distributed wind pattern.

Thus, to calculate the average power output potential of a site, it is necessary to have the actual probability distribution that describes the percent of time during the year that the wind is blowing at each speed. For each wind speed, the power is multiplied by the percent of time during the year that the wind blows at that speed, yielding the annual average wind power. The dependence of power output on patterns of wind speed makes site-specific measurements crucial to wind power station design.

[20] The equation used to calculate the amount of power in the wind is

$$\textit{Power} = \tfrac{1}{2} * \textit{air density} * \textit{wind velocity}^3 * \textit{swept rotor area} \quad \text{(Equation 1)}$$

Units are kilowatts (power), kilograms per cubic meter (air density), meters per second (wind velocity) and square meters (swept rotor area).

Table 3: Comparison of Wind Power Density at Three Sites with Identical Average Wind Speeds

Site	Annual Average Wind Speed (m/s)[a]	Annual Average Wind Power Density (W/m^2)
Culebra, Puerto Rico	6.3	220
Tiana Beach, New York	6.3	285
San Gorgonio, California	6.3	365

Example from PNL 1987, page 3.
[a] Speed given for 10 meter height.

Wind resource areas are defined based on their annual average wind power density. Table 4 shows the U.S. wind classification system for winds specified at 10 meter height.

Table 4: U.S. Wind Resource Classifications

Wind Resource Class	*Annual Average Wind Power Density (watts per square meter)*
1	0 – 100
2	100 – 150
3	150 – 200
4	200 – 250
5	250 – 300
6	300 – 400
7	400 – 1,000

Source: PNL, 1987, page 3. For winds specified at 10 meter height.

Another important wind characteristic is the change in wind speed with height, known as “wind shear.” In general, the wind blows at greater speeds with increased altitude. This means that the greater the height of the wind turbine, the greater the power output. From an economic standpoint, increasing height also means increasing costs. In practice, the choosing the optimum height of a turbine requires balancing these considerations.

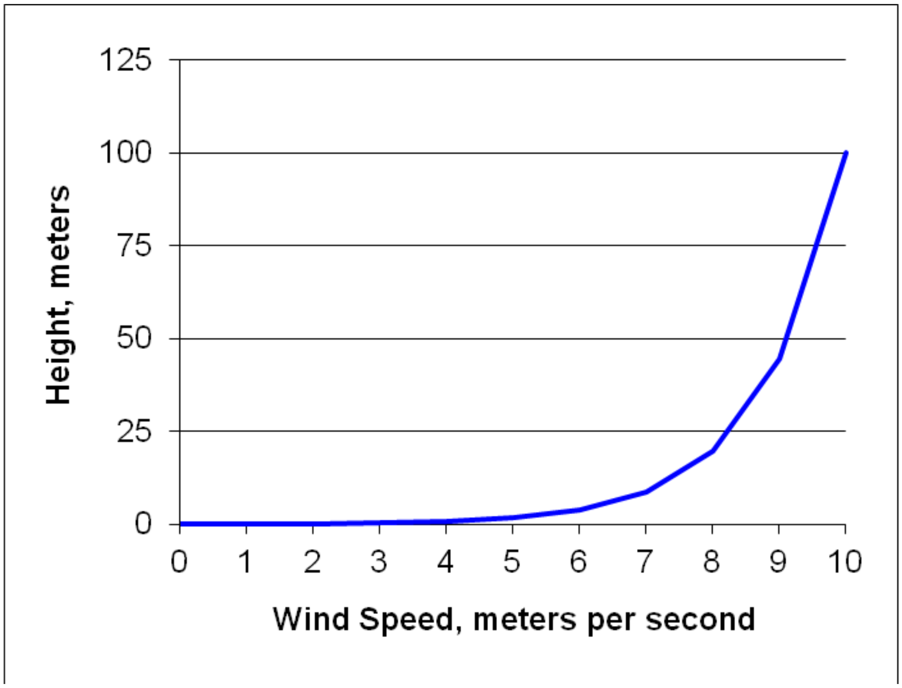
Wind speeds are generally lower at lower elevations because obstacles such as bushes, trees, and buildings create turbulence. Turbulence reduces the amount of energy that can be extracted by a wind turbine. “Roughness classes” have been developed to estimate the wind shear for different land surfaces. A summary of roughness classes is shown in Table 5. Figure 1 shows a wind shear profile for roughness class 1.

Table 5: Roughness Classes

Roughness Class	Relative Energy Index (%)	Roughness Length, *r*, (meters)	Landscape Type
0	100	0.0002	Water surface
0.5	73	0.0024	Completely open terrain with a smooth surface, e.g., concrete runways in airports, mowed grass
1	52	0.03	Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills
1.5	45	0.055	Agricultural land with some houses and 8 meter tall sheltering hedgerows with a distance of approx. 1250 meters
2	39	0.1	Agricultural land with some houses and 8 meter tall sheltering hedgerows with a distance of approx. 500 meters
2.5	31	0.2	Agricultural land with many houses, shrubs and plants, or 8 meter tall sheltering hedgerows with a distance of approx. 250 meters
3	24	0.4	Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain
3.5	18	0.8	Larger cities with tall buildings
4	13	1.6	Very large cities with tall buildings and skyscrapers

Source: DWTMA 1998, Reference Manual, Part 1.

Figure 1: Height vs. Wind Speed for Roughness Class 1



Curve shown is for roughness class 1. Assumed wind speed of 10 meters per second at 100 meter height. See Grubb and Meyer in Johansson et al., eds. 1993, page 160. Equation:

$$\left(\frac{velocity_1}{velocity_2}\right) = \left(\frac{\ln(height_1 / r)}{\ln(height_2 / r)}\right)$$

Another important source of turbulence is the wind turbines themselves. As the wind passes through the wind turbine, a wake forms behind the turbine. The wake disappears with increasing distance from the turbine, and wind speed recovers its normal value. This factor limits the number of wind turbines that can be installed per unit area of land, since sufficient space must be allowed around each turbine for the wind speed to recover its ambient value.

A measure of the loss of usable energy within a set of wind turbines is the "array efficiency." Table 6 gives an idea of the energy loss for two different size arrays at different spacing intervals. Precise estimation of the losses is complex, depending on terrain, meteorological conditions, and turbine characteristics, but the values in Table 6 are indicative of the magnitude of losses.

Table 6: Effect of Turbine Spacing and Number of Turbines on Array Efficiency

Arrangement of Turbines [a]	*Array Efficiency* [b] *for Turbines Spaced Every:* 5 Rotor Diameters	7 Rotor Diameters	9 Rotor Diameters
4 x 4	0.76	0.87	0.92
10 x 10	0.63	0.79	0.87

[a] The turbines are assumed to be arranged in a square. "4 x 4" means 4 rows of turbines with 4 turbines in each row.
[b] The "Array Efficiency" is an indication of the available energy from the wind for the given configuration compared to an equivalent number of machines without accounting for turbulence arising from the other turbines.
Explanation of chart: The entry "0.76" indicates that for a set turbines arranged in 4 rows with 4 turbines in each row, with a spacing of 5 rotor diameters between rows and 5 rotor diameters between each turbine in a row, the overall amount of energy is 76% of the amount of energy that would be predicted if the turbulence caused by other turbines were not taken into account.
Source: Grubb and Meyer in Johansson et al., eds. 1993, page 172.

Another consideration for wind power plants are extreme winds. In June 1998, a cyclone that hit the state of Gujarat destroyed roughly one-third of the over 300 wind turbines installed along the Saurashtra coast.[21] The damage to numerous wind turbines underscores the need for designs suited to such strong winds.

The intermittent nature of the wind is another important characteristic. Collection of wind data can help identify daily and seasonal patterns. Improved forecasting capabilities can help better integrate wind resources into energy systems. In our case study on Japan, we discuss the how an intermittent resource can be incorporated into near- and long-term energy systems.

Modern Wind Turbines

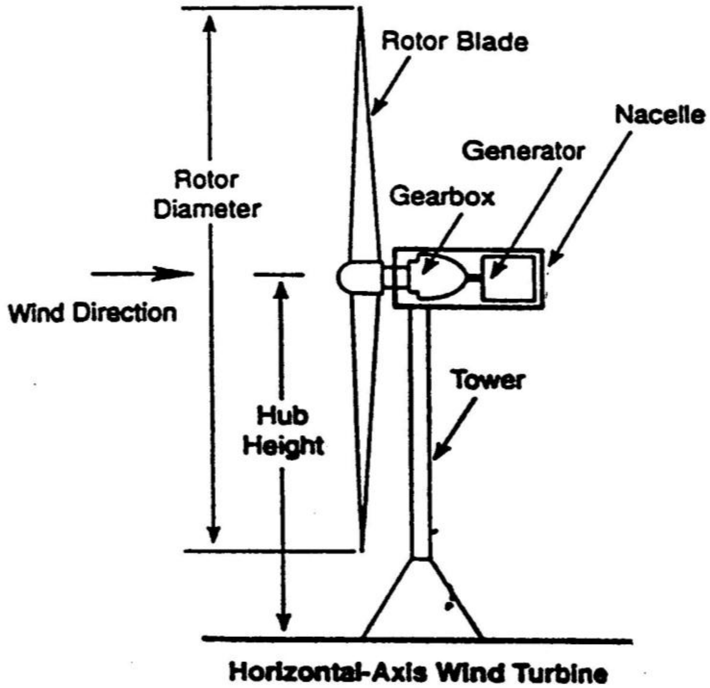
Many types of wind turbines have been designed and constructed. The most common commercial wind turbines sold today have blades that rotate on a horizontal axis. These "propeller-type" wind turbines are called horizontal axis wind turbines. There are several main features of such modern wind turbines[22]:

- The rotor, consisting generally of one to three blades mounted on a hub facing into the wind
- The yaw system, which positions the rotor perpendicular to the wind
- The drive train, including gearbox or transmission, hydraulic systems, and braking systems
- The electrical and electronic systems, including the generator
- The tower
- "Balance-of-station" systems, such as roads, grid interconnection equipment, etc.

Figure 2 shows some of these components.

[21] Harrison, Knight, Moller, 1998.
[22] Cavallo, Hock, and Smith, in Johansson et al., eds. 1993, pages 136-146.

Figure 2: Components of a Modern Wind Turbine



Source: NREL 1996.

The yaw mechanism uses electrical motors to turn the rotor into the wind. The wind turbine blades transfer the kinetic energy of the wind into a torque, or turning force, that turns the rotor hub. Wind turbines installed in the 1980s commonly had aluminum or steel blades. Wind turbines installed today use more advanced blade designs and materials such as fiberglass composite or wood-laminate.

The low-speed shaft of the wind turbine connects the rotor hub to the gearbox. Large (1 MW and greater) wind turbines rotate at around 12-22 revolutions per minute (rpm). The gearbox makes the high-speed shaft approximately 50 times faster than the low-speed shaft. The high-speed shaft drives the electrical generator. Key components of the wind turbine, including the gearbox and the electrical generator, are housed in the nacelle. Some offshore designs also place the transformer in the nacelle, as well as a crane for servicing.

The power output of the generator can be used directly, in which case only intermittent power could be supplied. Wind turbines can also be coupled with energy storage devices, which are currently too expensive to use other than in specialized applications such as for areas remote from electricity grids. Most commonly, modern wind turbines are connected to an electricity grid. Advances in electronics have reduced the cost of connecting wind turbines to grids. They have also made other improvements possible.

For instance, modern electronics enables the improvement of the quality of the wind electricity supply in times of highly variable or gusty winds.

The tower supports the nacelle and the rotor. Most early towers consisted of inexpensive steel lattices. For several reasons, the industry trend is toward tubular towers, even though they are more expensive than lattice towers. Tubular towers are safer for operation and maintenance personnel since an inside ladder (or an elevator) can be used to access the nacelle for maintenance. Also, "aesthetic" considerations are important –the visual impact made by the wind turbines on the landscape may be reduced with tubular towers. Additionally, wildlife considerations may also favor tubular towers since they do not provide attractive perches for birds that the lattice towers do.

Global Wind Electric Capacity

Installed capacity is shown in Table 7. About 12 countries had over 50 MW of installed wind capacity through the end of 1997. By the end of 2006, that number of countries is estimated to increase to 38.[23]

The ten largest wind turbine manufacturers in 1997 are shown in Table 8.

[23] AWEA 1997, page 5.

Table 7: Global Wind Electric Capacity, through 1997 and projections to 2006

Country/ Region	Estimated Capacity, end 1997	Projected Capacity, end 2006
USA	1,646	5,004
Canada	31	446
Mexico	2	507
Brazil	2*	1,142
Argentina	4*	699
Chile	0*	230
Peru	0*	260
Costa Rica	20*	110
Honduras	0*	60
Guatemala	0*	40
Caribbean	6*	81
Denmark	1,135	2,304
France	6	368
Germany	2,002	5,525
Greece	69	448
Italy	110	570
Ireland	51	441
Netherlands	349	1,233
Portugal	29	334
Spain	449	3,441
Sweden	123	555
UK	333	1,764
Former Soviet Union	28	1,030
Turkey	0*	325
China	179	1,907
India	870 (Note 1)	4,054
Philippines	0*	105
Japan	15*	331
New Zealand	14*	184
Australia	3*	163
World Total	*7,679*	*35,984*

Units are MW. Sources: 1997 data from DWTMA 1998, Table 19: Wind Turbine Markets, except * figures (countries for which estimates are not specified in DWTMA 1998) are estimates from AWEA 1997. Projections for 2006 from AWEA 1997. World Totals for both years include regions not shown.
Note 1: The figure for India is uncertain, as some capacity may not be operative. One source notes that some capacity reported as "installed" may have been in fact only planned (DWTMA 1998, Table 19.)

Table 8: Major Wind Turbine Manufacturers, 1997

Manufacturer	Country	MW Installed During 1997	Market Share
Vestas [1]	Denmark	383	24.5
NEG Micon [2]	Denmark	309	19.7
Enercon	Germany	223	14.2
BONUS	Denmark	222	14.1
MADE	Spain	75	4.8
Nordex	Denmark	67	4.3
ENRON [3]	USA / Germany	67	4.3
Desarrollos	Spain	54	3.4
Wind World	Denmark	29	1.9
WindMaster	Netherlands	26	1.6
Other manufacturers	-	87	5.6

Source: BTM 1998.
Notes:
[1] Includes sales from associated companies (Gamesa Eólica, Vestas RBB India).
[2] Merger between Micon and Nordtank Energy Group.
[3] Both Tacke (Germany) and Zond (USA) are owned by Enron Wind Corporation.

Advantages and Disadvantages of Land-based Wind Energy

Wind has several important advantages as an energy source. It has a very large resource base and it is widespread. It is a renewable that does not leave a burden to future generations. Electricity production from wind energy also does not result in emission of large amounts of greenhouse gases. In the Kyoto Protocol industrialized countries agreed to reduce greenhouse gas emissions by an average of 5% below 1990 levels by around 2010 as means of hopefully avoiding changes to global climate systems.[24] There are some emissions of the greenhouse gas carbon dioxide (CO_2) attributable to wind power (as a result of electricity consumed during manufacturing of the turbines), though the lifecycle emissions of CO_2 from wind turbines are estimated to be less than 1 percent of those from coal power plants.[25] The American Wind Energy Association estimates that each 10,000 MW of wind energy would replace 21 million metric tons of CO_2 emissions per year (5.6 million metric tons of carbon per year), based on replacement of the U.S. average fuel mix.[26] Other air pollution emissions, such as sulfur dioxide and particulate matter, are also essentially eliminated by using wind energy. Other environmental benefits of wind power include elimination of the wastes associated with fuel production and use associated with both from fossil and nuclear fuels.

[24] The Kyoto Protocol is the agreement made in December 1997 at the Third Conference of the Parties to the United Nations Framework Convention on Climate Change. Six kinds of greenhouse gases are covered by the agreement: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride.
[25] AWEA 1998b, footnote 1.
[26] AWEA 1998b, footnote 4.

Wind power systems are flexible and can be developed on a large-scale and also on scales appropriate for small electricity grids. Single wind turbines serving individual customers are also possible though this requires significant additional investments in energy storage for reliable power supply. Wind capacity can be added incrementally and quickly, avoiding costs associated with unused capacity or finance charges during long construction periods. Manufacture of wind turbines can also take place locally if deemed necessary or desirable. Wind power also does not create weapons-usable or other radioactive materials. There are no environmental impacts associated with fuel production and processing (in contrast to significant impacts caused by coal, oil, and nuclear fuel production and processing), since the "fuel" is provided for free. Finally, wind power does not have high intergenerational impacts.

Wind power also has disadvantages that have prevented greater development of the industry. In the late 1970s, there was no established wind industry, and the first obstacles to overcome were unreliable and immature technology and high costs. With time, wind turbine technology has dramatically improved and costs have come down. The negative impression left by early efforts – such as noisy and broken down machines – still lingers, however.

The main disadvantages of land-based wind power generation can be grouped into two categories – the economics of wind energy and issues associated with siting wind turbines. Economic issues include the generally higher cost of wind energy relative to highly-efficient natural gas power plants and the fact that wind is an intermittent energy source whose availability cannot be adjusted to meet variable demands for electricity without costly investments in energy storage devices unless it is connected to a diverse grid. Siting issues include large tracts of land necessary for spacing out wind turbines, impacts on ecosystems (most important to date have been bird deaths), visual impacts, avoidance of residential areas, and impacts from road construction and erosion.

The main advantages and disadvantages of land-based wind energy are listed in Table 9.

Siting Issues

Several siting issues associated with wind turbines can be straightforwardly resolved. Erosion and impacts from road-building can be avoided or mitigated with proper construction techniques. Concerns about noise, problematic for earlier turbines, have largely been resolved through better design and siting practices – noise levels from modern wind turbines are around 45 dB at 100 meters distance. With proper siting practices, noise impacts can be effectively minimized. Visual impacts can be reduced by the use of tubular instead of lattice towers, by using different size turbines, and appropriate wind farm layout. Abandoned wind turbines can be addressed by provision of funds for decommissioning. Proper attention to these aspects of wind farm development can help avoid these negative environmental consequences.

Table 9: Advantages and Disadvantages of Land-based Wind Energy

Advantages	Disadvantages
Renewable resource	Intermittent resource – requires integration with an electricity grid and or storage technologies
Large resource base	Turbines must be spaced over a large area
Essentially no intergenerational impacts, straightforward decommissioning	Incompatible with some land uses, e.g., wilderness, forests, areas with high population density
Compatible with some land uses, e.g., ranching	Visual impacts
Widespread, though not always economically-competitive or	Wildlife, especially birds, may be impacted
Very low greenhouse emissions	
No water, air pollution (except from manufacturing)	
Compatible with small- and large-scale grids as well as remote power systems	
Capacity can be added incrementally	
Short project times	
No nuclear proliferation consequences	
No catastrophic accident potential	

Although the wind resource is widespread, the best resources are not always next to existing transmission lines. In these cases, extra costs will be incurred for access lines and power substations. A 115-kilovolt access line costs $143,000 to $428,000 per mile, depending on the specific conditions.[27] Substation costs will also be required; costs for connection to an existing versus new 115-kilovolt substation are estimated at $360,000 and $1,080,000, respectively. However, the wind resources near transmission lines in the United States are substantial, and turbines installed in many of these areas would incur low incremental costs. One study concluded that although there are site-specific transmission issues, the "proximity of wind resources to transmission lines does not overly constrain wind energy development in the United States." [28]

The effects on wildlife, especially birds, have caused serious problems in certain locations. Two of the most notable problems have been bird deaths at Tarifa, Spain (which lies along a major bird migration route across the Mediterranean Sea)[29] and deaths of golden eagles, a federally-protected species, in Altamont Pass, California. The latter area, the site of the world's first large-scale wind farm, has one of the world's highest concentrations of golden eagles. Studies by the University of Santa Cruz Predatory Bird Research Group estimated that of 80 golden eagles deaths during a several year period,

[27] Doherty 1995, page xii. 1993 dollars.
[28] Doherty 1995, page xiv.
[29] NWCC 1997.

one-third to one-half of the deaths were associated with electrocution or collision with wind turbines.[30]

It is anticipated that replacement of older turbines (installed in the early 1980s) and redesign of windfarms at Altamont Pass could result in a great reduction or elimination of eagle and hawk deaths. In one project, some 644 turbines (100 kW each) will be replaced with 92 larger turbines (700 kW each) as part of a "repowering" project.[31] Avian studies have also helped to identify areas attractive to the birds, such as steep hillsides, that will be avoided in the new layout. The combination larger turbines (which have slower rotational speed), better turbine placement, and fewer turbines may mitigate the situation. Other mitigation steps may include bright white blades and underground wiring. Carrying out preliminary environmental studies and continued monitoring of ecosystem impacts should be a standard feature of wind projects, especially for projects at larger scales.

Possibly the most important disadvantage of land-based wind power is that the energy available per unit land area is low. As a result, wind power requires far larger land area than many other energy sources, notably fossil fuels or nuclear energy. Some of the land impact is reduced by the fact that the turbine base itself occupies relatively little land (turbines are spaced out so that the turbine blades do not create undue turbulence for nearby turbines). Land uses such as grazing are compatible with wind turbines and can take place up to the turbine base.

Although many countries will be able to generate significant amounts of wind electricity with modest impacts on the land, space requirements may prevent other from developing significant wind capacity. Problems with the area required for proper spacing of wind turbines are likely to be more acute in countries with high population densities. This appears to be the case in Denmark, where the Danish Energy Agency has raised concern about the potential for "an extremely negative effect on the landscape and the environment" associated with large-scale wind energy development.[32] The solution proposed in Denmark is development of offshore wind energy. Development of offshore wind resources can largely or wholly resolve siting and environmental disadvantages of wind power in densely populated areas such as much of Europe and Japan.

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[30] Davidson 1998, page 37.
[31] AWEA 1998c, page 6.
[32] Danish Energy Agency 1997.

2. Offshore Wind Energy

Development of offshore wind energy resources offers the prospect of avoiding the most severe impact of land-based wind power – large stretches of land required for spacing out wind turbines. Although offshore construction involves additional costs, these are at least partly offset by more constant winds and higher wind speeds, as well as elimination of land acquisition costs. Less turbulent winds result in less turbine wear and therefore longer turbine life. Visual impacts can be reduced or eliminated by offshore wind turbine siting and there are no concerns about placement of wind turbines near human settlements. However, offshore wind turbine siting is not free of possible adverse impacts. These include potential impacts on shipping lanes and on marine ecosystems.

The First Offshore Projects

The concept of offshore wind power was advocated by Professor Heronemus of the University of Massachusetts in the 1970s.[33] However, practical generation of electricity from offshore wind power has only been achieved since the early 1990s. As of the end of 1997, six offshore wind projects were operational in three countries, as shown in Table 10. The total capacity in 1998 was only about 25 megawatts, compared to land-based projects of well over 9,000 MW at year's end. The offshore capacity is in Denmark, the Netherlands, and Sweden. Current offshore projects were developed as pilot-scale or demonstration projects. They were also installed relatively close to the coastline (between one and six kilometers) and in protected waters. Over the next several years, the amount of installed offshore capacity is expected to rise dramatically as Denmark proceeds with its ambitious offshore program (see discussion below) and as additional countries such as Germany and the U.K. install their first offshore projects. One offshore project (a small project of two turbines) won a bid in a U.K. program to promote renewable energy; the project is expected to be on-line in 1999.[34] In addition, 65 MW worth of capacity have been proposed for two other sites.

Table 10: Operational Offshore Wind Projects, 1998

Location	Number ; Size of Turbines	Total Capacity, MW (nameplate)	Year	Country
Nogersund	1 @ 220 kW ea.	0.22	1990	Sweden
Vindeby	11 @ 450 kW ea.	4.95	1991	Denmark
Lely (Ijsselmeer)	4 @ 500 kW ea.	2.0	1994	Netherlands
Tunø Knob	10 @ 500 kW ea.	5.0	1995	Denmark
Dronten I (Ijsselmeer)	19 @ 600 kW ea.	11.4	1996	Netherlands
Bockstigen	5 @ 550 kW ea.	2.75	1997	Sweden

Source: BTM 1998, page 42.

[33] See, for example, Heronemus 1972, Heronemus 1973a, and Heronemus 1973b.
[34] Border 1998, page 7.

The cost of electricity from offshore wind farms has decreased over time, from about 8.8 – 9.9 ¢ per kWh (0.08 – 0.09 ECU per kWh) for the first projects, to about 5.5 ¢ per kWh (0.05 ECU per kWh) for the 1997 Bockstigen project in Sweden.[35]

The offshore wind turbines have performed well. Quarterly production data for January – March 1998 are summarized in Table 11.[36] A 1997 report noted that the Danish offshore wind farms "function well from the technical point of view."[37] At the Tunø Knob site in Denmark, the availability of the turbines was 98% during the first 20 months of operation.

Table 11: Production Data from Offshore Wind Turbines – 1st Quarter 1998

Location (Country)	*Turbine size (kW)*	*Quarterly Capacity Factor*	*# of Turbines Included in Data*
Nogersund (SE)	220	0.25	1
Vindeby (DK)	450	0.39	11
All 450 kW wind farms on land (DK)	*450*	*0.28*	*31*
Lely (NL)	500	0.17	4
Tunø Knob (DK)	500	0.43	10
All 500 kW wind farms on land (DK)	*500*	*0.31*	*56*
Dronten I (NL)	600	0.35	19
Bockstigen (SE)	550	*	*

Source: WindStats 1998.
* Data not reported for Bockstigen.

Physical Considerations for Offshore Wind Development

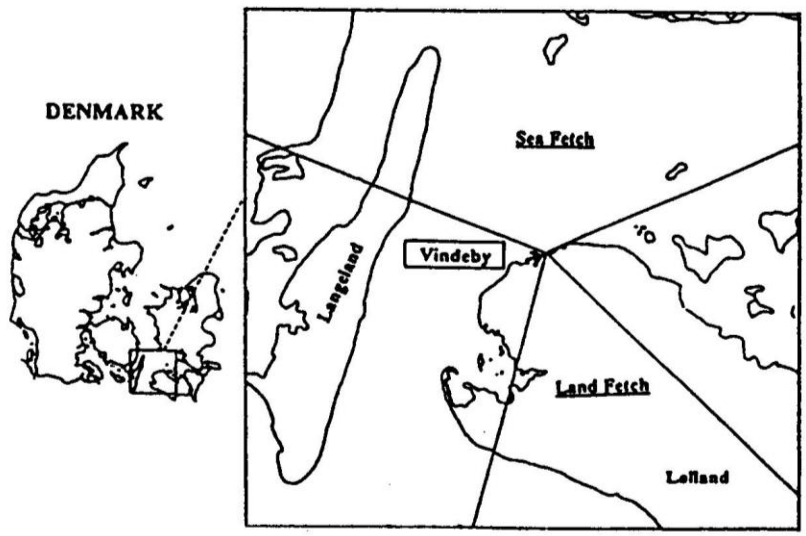
There are important differences between conditions on land and those offshore – most importantly the "roughness" of the surface (see Table 5). The roughness of the surface for several kilometers upwind of a wind turbine has a measurable effect on the wind speed profile and turbulence intensity.[38] The smooth surface of the water leads to several advantages if wind turbines are located offshore.

Areas upwind of a turbine can be divided into sections according to the type of surface. Sections where the wind blows over the sea are referred to as "sea fetch" and sections where the wind blows over the land are referred to as "land fetch." Each has different wind speed vs. height profiles. Figure 3 shows a depiction of the Vindeby site. It can be

[35] Costs as calculated in Kühn et al. 1998 using standard assumptions of 5% discount rate, 20 year loan, and conversion of $1 US roughly equal to 0.9 ECU. Note: one ECU is worth a little less than one euro, as of January 1999.
[36] Historical production data from turbines is available from a number of sources, including *WindStats Newsletter* (mainly European Wind Turbines) and the California Energy Commission (turbines in California).
[37] ELKRAFT 1997, page 11.
[38] Barthelmie et al. 1996, page 194.

seen that in the north, the fetch is mostly sea, in the south, mostly land, and in the east and west a mixture of land and sea fetch.

Figure 3: Wind at the Vindeby Site



Source: Barthelmie, et al. 1996, page 193.

One advantage of sea fetch is an increase in wind speed; increases of 5 to 45 % have been suggested by various studies.[39] One study estimated a sharp increase in the wind speed of 10% at a distance 3 kilometers from the shoreline at the Vindeby site, thereafter increasing at a slower rate.[40] Since wind power increases as the cube of the wind speed, the increase in power resulting from an increase of 10% (for example) is significant.

A second advantage of a sea fetch is that offshore winds are less turbulent than onshore winds. Greater turbulence results in decreased energy output and greater stress ("fatigue") on turbine components such as blades. The "turbulence intensity" is the ratio of the wind speed standard deviation to average wind speed over a given interval of time.[41] Studies at the Vindeby site found lower turbulence at offshore sites. Turbulence intensity for offshore sites, averaged for winds from all directions, was 0.105, compared to a turbulence intensity of 0.117 at a nearby site located on land.[42] Since only a fraction of the fetch in the Vindeby studies is truly a sea fetch (see Figure 3), the turbulence intensity for sites further offshore is likely to be even lower. Reduction in turbulence intensity with distance from shore may thus offset some the increased costs for undersea cabling and more difficult access if turbines are located further from shore.

[39] Barthelmie et al. 1996, page 191.
[40] Barthelmie et al. 1996, page 208.
[41] Cavallo, Hock, and Smith, in Johansson et al., eds., 1993, page 126.
[42] Barthelmie et al. 1996, pages 200-201. For comparison, the turbulence measured at San Gorgonio pass, California, was 0.29. Sites with a turbulence intensity of greater than 0.5 are generally considered too windy to install wind turbines. (Cavallo, Hock, and Smith, in Johansson et al., eds., 1993, page 126)

Third, low roughness results in a low wind shear. This means that the hub height can be decreased to achieve a given wind speed or conversely that wind speed will be higher for a given hub height. In practice, this may result in a lower height for an optimized design. For example, one study found that an optimized wind turbine at Rødsand (one of the five 150 MW offshore sites currently being planned in Denmark) would have a hub height of 48.4 meters, which is 13.9 meters lower than a comparable wind turbine located on land.[43]

The greater offshore atmospheric stability has a down-side, however. The turbulent wake generated from the turbines themselves will dissipate more slowly compared to onshore turbines.[44] This may lead to a greater spacing between offshore wind turbines compared to those on land. The spacing chosen must balance the benefits of reduced turbulence from the turbines with increased costs due to longer undersea cabling distances.

Offshore wind conditions – higher wind speeds, less turbulence, and less wind shear – can result in greater energy capture, and optimized designs to take advantage of them can help offset the added costs of offshore installation. The Rødsand study found that for that site, an optimized offshore wind turbine would have an annual average energy output 32% higher than an optimized wind turbine on land.[45]

However, operation in the offshore environment also creates significant engineering challenges. The offshore structure must not only be designed to withstand extreme winds, like their onshore counterparts, but also extreme wave forces and, in some locations, floating ice. In addition to the need to withstand the magnitude of the different forces, the structure must be designed so that its natural (resonant) frequency does not match the frequency of wind or water loads. If the natural frequency of the structure matches the environmental frequencies, the resonant vibrations of the structure can grow until the structure breaks.

There is a significant effort to design of support structures that can accommodate such forces. Several studies have been carried out under the European Commission's *Structural and Economic Optimisation of Bottom-Mounted Offshore Wind Energy Converters* (Opti-OWECS) project.[46] Support structures have accounted for some 33% of the investment cost of offshore wind farms.[47] The "support structure" includes the tower and the means of anchoring it in the water. Although floating concepts have been suggested[48], only "bottom-mounted" units have been installed to date. In the future, floating systems may allow exploitation of wind energy in areas with deeper water. The development of offshore wind power in deep waters is likely to benefit a great deal from collaboration between government, the private wind industry and the petroleum industry,

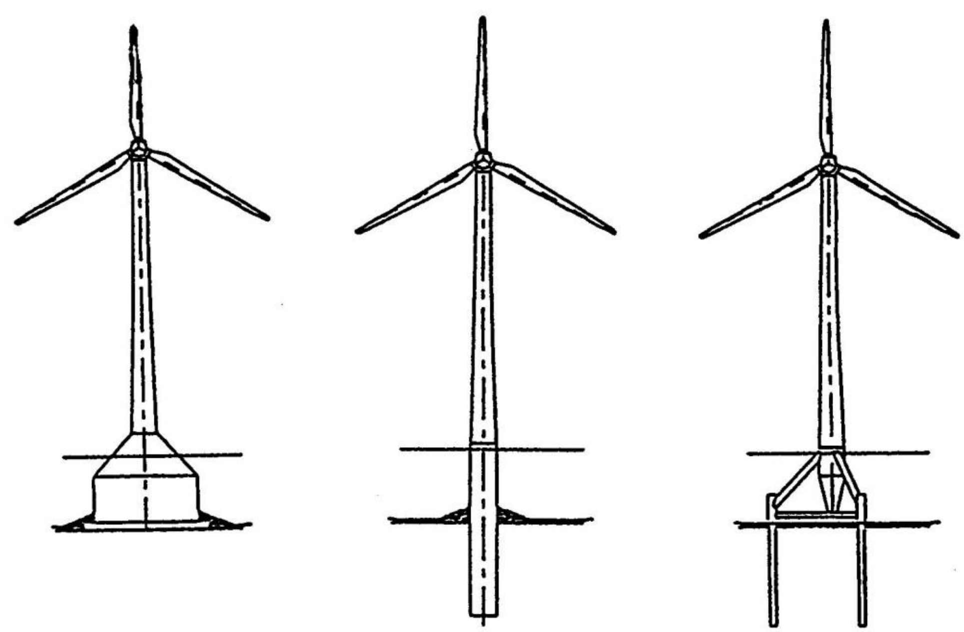
[43] Fuglsang and Thomsen 1998, page 26. 2 MW wind turbine assumed.
[44] Kühn and Bierbooms 1996, section 4.5.
[45] Fuglsang and Thomsen 1998, page 26.
[46] The project is funded in the framework of the Non Nuclear Energy Programme Joule III.
[47] Kühn et al. 1996.
[48] See, for example, Halfpenny et al. 1995.

the latter having the most experience in offshore platforms. In Europe such collaboration is already taking place.

There are several types of "bottom-mounted" designs that have been used or proposed. Early offshore wind farms (Vindeby, Tunø Knob) used large concrete caisson foundations. These structures were floated out to the desired location, then filled with dense material to sink them to the sea floor. In such structures, gravity provides stability against wind, water, and ice. Although straightforward to construct, a major disadvantage is that at greater depths, the concrete foundations become prohibitively heavy and expensive. Additionally, a limiting factor is that a site near the offshore location is required for construction of the concrete caissons.

Solutions to the limitations of concrete caisson foundations have been found by enlisting the aid of experts in the offshore construction industry.[49] Several other types of foundations are shown in Figure 4.

Figure 4: Types of Foundations



Steel-gravity *Monopile* *Tripod*

Source: Rambøll 1997.

The steel-gravity foundation uses a light weight steel frame with a center column. The base of the steel structure is filled with high density material as ballast. The "monopile" foundation consists of a steel pile (3.2 meter diameter, wall thickness 35 to 60

[49] Details on offshore foundations taken from Rambøll 1997.

millimeters) driven some 10 to 20 meters into the seabed, depending on the geology of the site. The turbine tower is then bolted to the monopile. A third concept is a "tripod" foundation, consisting of a steel frame that is anchored by three steel piles (0.9 meter diameter, wall thickness 16 to 43 millimeters) driven into the seabed at the corners.

The optimal foundation will depend on a number of factors. Depth is a key consideration, with tripod foundations generally better suited for greater depths. Also, some seabeds, especially areas with boulders, may not be suitable for pile-driven foundations. Sites prone to seabed erosion may be more problematic for gravity-based foundations than for piled foundations. For shallow locations with floating ice, gravity structures may be more desirable. Although costs between different types of foundations varied significantly, an engineering study concluded that the best approach for a given location and environment may depend on considerations other than cost.[50]

Larger turbines are crucial in order to make offshore wind farms economic. As shown in Table 10, existing offshore wind turbines are rated 450 to 600 kW. However, costs of foundations for much larger turbines do not rise in proportion with the size of the turbine and in industrialized countries readily-available installation equipment such as cranes and barges can handle the larger turbines as easily as smaller ones.[51] Thus, the larger the turbine, the lower the foundation cost per unit of installed capacity. The next set of offshore turbines will likely be 1.5 MW, possibly larger; several studies postulate turbines of 3 to 4 MW eventually being installed in large offshore wind farms.[52]

The accessibility of offshore wind farms is another important issue requiring careful attention.[53] Harsh weather may significantly limit access to offshore wind farms. Additionally, the cost of operation and maintenance activities is more expensive than equivalent tasks on land. Because of these issues, operation and maintenance strategies need to be taken into account during the design of turbines, support structures, and layout of the windfarm. If not, the resulting availability could be unacceptably low. One study found, in fact, that it is "economic to invest a relatively high amount of capital in order to achieve high and reliable energy output."[54]

Denmark's Plan for Offshore Wind Energy

Commercial energy use in Denmark in 1995 was approximately 20.5 million metric tons of oil equivalent.[55] It has relatively high emissions of carbon dioxide per capita, about 10.8 metric tons (2.9 metric tons of carbon).[56] One reason for this is a heavy dependence

[50] Rambøll 1997, Section 8.
[51] Rambøll 1997, Section 8.
[52] For example, Ferguson 1997 and Kühn et al. 1998.
[53] Van Bussel and Schöntag 1997.
[54] Kühn et al. 1998, page 25.
[55] World Bank 1998, Table 3.7.
[56] World Bank 1998, Table 3.8. The 10.8 metric tons per capita for 1995 is down from 12.3 metric tons per capita in 1980.

on coal for electricity – approximately 75% of electricity in Denmark in 1995 is derived from coal.[57]

In 1990, Denmark established a goal of 20% CO_2 emission reduction by 2005 as compared to 1988 emissions.[58] Denmark's *Energy 21* plan sets out even more ambitious objectives for sustainable energy development. A centerpiece of *Energy 21* is a goal of cutting 1988 CO_2 emissions in half by the year 2030.[59]

Wind power is scheduled to play an important role in achieving the goals of *Energy 21*. A total of 5,500 MW of wind turbines are projected to be installed by 2030 in Denmark, about 75% of which are expected to be installed offshore.[60] If achieved, the total wind power generation would be about 50% of total electricity generation and 25% of total energy consumption in Denmark. In 1998, wind energy supplied more than 8% of Denmark's electricity.[61]

Major changes from the first offshore projects will likely include larger turbines (an increase from roughly 500 kW turbines to 1.5 to 2.0 MW turbines), greater distances from the coast (most turbines will be located at distances greater than 7 kilometers from land), and larger project size (an increase from 5 MW to 150 MW per project). Other likely changes include different types of foundations, development of more cost effective operation and maintenance strategies, and still larger turbines.[62]

Denmark's 1997 *Action Plan for Offshore Wind Farms in Danish Waters* concluded that it was possible to produce electricity from the first large-scale offshore wind farm demonstration projects at the same average price as moderately good, land-based wind turbines operated by utility companies – about 5.1 to 5.5 ¢ per kWh (using currency exchange rates).[63] These estimates did not include additional costs that might be incurred in order to accommodate an intermittent power supply in the operation of electricity grids. In September 1997, the Danish Minister for Energy and Environment and the Danish utilities signed an agreement to develop 750 MW of offshore wind power between 2000 and 2008 as a demonstration of larger offshore wind farms.[64] Five projects of roughly 150 MW each are projected. In addition, a smaller project of 20 turbines, with a total capacity of 30 to 40 MW, located near the city of Copenhagen (on the Middelgrunden sand bank), is planned for operation in 2000.[65]

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[57] World Bank 1998, Table 3.9.
[58] Danish Energy Agency 1996, Foreword.
[59] Danish Energy Agency 1996, Section 1.3.
[60] ELKRAFT 1997.
[61] Worldwatch 1999.
[62] Kühn et al. 1997, Van Bussel and Schöntag 1997.
[63] ELKRAFT 1997, page 8. Source cites 0.35 to 0.38 Danish kroner (DKK) per kWh. Using the 1997 purchasing power parity conversion of 8.53 DKK equal to $1 US, the cost of electricity is 4.1 to 4.5 ¢ per kWh. Purchasing power parities published in OECD 1998.
[64] Danish Energy Agency 1997.
[65] *Windpower Monthly*, September 1998, page 16. Plans originally called for 27 turbines of 1.65 MW each, to begin operation in 1999, but the project has been scaled back to twenty machines, due to concerns about visual impact, and delayed by about one year.

The criteria for identifying suitable locations to install the total expected 4,000 MW of offshore wind turbines by the year 2030 included areas more than 7 kilometers from the coastline (this minimum distance was set to avoid visual impacts from land) and areas with water depths of up to about 10 meters. Additional considerations were made to exclude national park areas, shipping routes, military zones, and other areas deemed incompatible with wind development. Four main sites have been identified as the most promising, with a total realizable potential of 3,600 MW if the maximum water depth is set at 10 meters, or 7,850 MW if depths up to 15 meters are considered.[66] In addition to these 4 main sites, "supplementary sites" have been identified with a realizable potential of 2,060 MW if the maximum depth is set at 10 meters, or 4,370 MW if maximum depth is set at 15 meters. This orderly approach to wind energy development will be valuable in pursuing Denmark's energy and environmental goals.

Costs of Offshore Wind Electricity

The costs of electricity from the first offshore wind farms have decreased with time, as have the projections of costs for future projects. The first two offshore projects, Vindeby (1991) and Lely (1994), are calculated to have electricity costs of about 9.3 ¢ per kWh (0.085 ECU per kWh).[67] The Bockstigen project, completed in 1997, is estimated to have electricity costs of 5.4 ¢ per kWh (0.049 ECU per kWh).

For Vindeby and Lely, investment costs were broken down roughly as follows: 35 to 40% for the wind turbine, 33% for the support structure, and 10 to 20% for grid connection.[68] Additionally, operation and maintenance costs are estimated to be about 1.1 ¢ per kWh to 1.3 ¢ per kWh.[69]

The theoretical promise of offshore wind has been given substance by the performance of pilot scale projects. For example, the Bockstigen project has already achieved economically-attractive costs. But there is still more practical experience needed to achieve favorable economics for offshore wind power because projects have yet to be built on a significant scale at distances of 7 to 40 kilometers. Further, the largest commercially available wind turbine as of 1998 was rated at 1.65 MW, whereas most optimization studies indicate a desirable size of 2 to 4 MW per turbine for offshore conditions. Thus, while the early offshore projects have served to spark interest in offshore wind power, the projected costs need to be verified by development at larger scales. This is scheduled to happen in the next few years in Denmark at least.

A number of optimization studies have been carried out to try to reduce the cost of offshore wind electricity. Future offshore wind farms will have larger turbines, lower relative hub heights, steel foundations, and will be based on more extensive structural

[66] ELKRAFT 1997, page 13. Higher, "theoretical," estimates were initially made. The "realizable" fraction cited in the text accounts for considerations such as dividing the wind farms into visually separate units.
[67] Kühn et al. 1998.
[68] Kühn et al. 1996.
[69] Kühn et al. 1998.

reliability calculations than those that exist today. As noted above, a July 1997 report by the Danish Energy Agency and the Danish Utilities concluded that the costs for the first five planned offshore projects will be 0.35 to 0.38 DKK per kWh.[70] A study by Risø National Laboratory concluded that the cost of electricity from the planned Rødsand (Denmark) offshore site would have costs equivalent to electricity from a stand-alone onshore wind turbine.[71]

The Opti-OWECS study found that offshore wind energy is "fully viable."[72] The used an integrated design approach based on currently-available technology. The Opti-OWECS study estimated costs of 5.6 ¢ per kWh (0.051 ECU per kWh) assuming 8.4 meters per second annual average wind speed (60 meters height), with a 30% capacity factor.[73] The study noted that this wind speed was "rather conservative" compared to other studies. Lower costs, of 4.8 ¢ per kWh (0.044 ECU per kWh), were estimated assuming 9.0 m/s wind speed and 34% capacity factor.[74] In the development of a design solution within the Opti-OWECS study, a two-blade, 3 MW machine is assumed. Specific capital costs are $1,360 per kW (1,240 ECU per kW). An economic lifetime of 20 years and a discount rate of 5% was used. A summary of the initial capital costs (investment costs) and the cost of electricity for the 8.4 m/s case are shown in Table 12.

Table 12: Estimated Cost Breakdown for Offshore Wind Farms Installed in Mid-2000's

Cost Component	Percent of Initial Capital Cost
Wind Turbine	45
Support Structure	25
Power Collection	13
Offshore Power Transmission	8
Installation	7
Project Management	2

Cost Component	Percent of Levelized Cost of Electricity
Wind Turbine	35
Support Structure and Installation	24
Operation and Maintenance	22
Offshore Grid Connection	15
Decommissioning	2.5
Project Management	1.5

Source: Kühn et al. 1998, Figures 15 and 16. Annual mean wind speed 8.4 m/s, 20 year lifetime, 5% discount rate.

[70] ELKRAFT 1997, page 8. Equal to 5.1 to 5.5 ¢ per kWh using currency exchange rates and 4.1 to 4.5 ¢ per kWh using purchasing power parity conversion.
[71] Fuglsang and Thomsen 1998, page 29.
[72] Kühn et al. 1998, page 30.
[73] Kühn et al. 1998, page 23.
[74] Kühn et al. 1998.

Further improvements in the economics may be possible if longer lifetimes can be achieved. Lower turbulence may help to extend the lifetime of some components. It is unlikely, however, that significant increases will be achieved for certain components such as the blades. But it may be possible to design foundations and towers for a 50 year lifetime. This would mean that even with a major overhaul of the blades and other parts of the turbine at 20 to 25 years, the cost of electricity would be significantly reduced because large capital costs for the support structure would be spread over the 50 year period.

Other Considerations for Offshore Wind Farms

Area Required for Offshore Wind Power

A study of the Rødsand, Denmark, site assumed 100 turbines (2 MW each with a rotor diameter of 74 meters) with a spacing of 5 rotor diameters perpendicular to the predominant wind direction, and a spacing of 14 rotor diameters along the predominant wind direction.[75] This gives a power density of 5.2 MW per square kilometer. Conversely, 0.2 square kilometers of ocean would be required for 1 MW of wind power.

A spacing of 10 diameters by 10 diameters is used in a more general study of offshore wind potential in northern Europe.[76] An assumed rotor diameter of 80 meters is used. At a spacing of 10 diameters by 10 diameters, a gap of 800 meters would exist between adjacent turbine towers. This arrangement yields a power density of 3.1 MW per square kilometer.

Impact on Ecosystems

Studies of fish and bird life near the offshore wind farms have been undertaken. At the Vindeby, Denmark, site, it was found that the amount of fish increased after installation of the wind turbines.[77] The foundations serve as an artificial reef where mussels can grow, encouraging growth of other flora and fauna. Bird studies were not carried out since few birds use the area.

An extensive study of birds at the Tunø Knob, Denmark, site was carried out over a period of three years by the National Environmental Research Institute in Kalø, Denmark.[78] Of concern were a large population of eiders, a species of diving duck, in the area. About 40% of the North Atlantic eider population winters in the Danish part of the Kattegat Sea. The ducks use the shallow areas (up to 10 meters) as winter feeding grounds, a time when other areas are frozen. The three-year study found that the birds generally avoided coming within 100 meters of the turbines. At Tunø Knob, the ten turbines are arranged in two rows of five turbines each. The study concluded that there was no significant adverse impact of the turbines on the birds. It should be noted,

[75] Fuglsang and Thomsen 1998.
[76] Kühn et al. 1998.
[77] Krohn 1998.
[78] DWTMA 1998, "Birds and Offshore Wind Turbines."

however, that other environmental changes were occurring during the three-year study period at Tunø Knob, requiring careful extrapolation of the results. Specifically, a decline in small blue mussel populations (the eider's preferred prey) in a wide area around Tunø Knob led to fewer ducks than observed in the year before construction of the wind farm. Thus, the interaction of a population of ducks over a period longer than the study with the wind turbines remains to be determined.

Preliminary results of studies of wind turbines on the I Jsselmeer, an important wetlands habitat in the Netherlands, have found that ducks can be adversely affected by wind turbines.[79] Investigation into the causes and development of mitigation steps should be implemented as part of future offshore wind energy programs.

Future development of wind farms is expected to take place at a much greater scale than has occurred to date (groups of hundreds of turbines, as opposed to clusters of 10 or 11). Large scale development may create places for some species to breed to the disadvantage of others, possibly changing near-shore ecological balances in unforeseen ways. The ecological and economic impacts of offshore wind energy use may be complex. Given the positive as well as potential adverse impacts, the ecological consequences of installing offshore wind power plants over large areas near the coast need to be examined in detail. This will require the development of offshore wind demonstration projects on a significant scale. One important advantage of wind power development is that the adverse ecological impacts can, in all probability, be reversed by timely action, if those impacts are found to be unacceptable.

The same cannot be said of some of the most important adverse impacts of nuclear or fossil energy. For example, the offshore impacts of plutonium fuel production are large, long-lasting, and generally irreversible. The British Nuclear Fuels Ltd. reprocessing plant in northwestern England has polluted the Irish and North Seas and made the marine life radioactive.[80] Even pigeons in the area have become radioactive.[81] Thus, even on the issue of impacts on avian life, the consequences of offshore wind power development are likely to be far lower than those of plutonium separation. And offshore wind power development may have positive impacts, such as creation of artificial reefs for marine life.

[79] Harrison 1996.
[80] REUTERS 1998.
[81] MAFF 1998.

3. Case Study – Wind vs. Plutonium in Japan

Energy and Electricity in Japan

Japan's total primary energy supply in Fiscal Year 1994 was equivalent to 577 million kiloliters of oil equivalent.[82] About 57.4 percent of this came from oil, 16.4 percent from coal, and 11.3 percent from nuclear. Most of the remainder came from natural gas. Japan is largely dependent on imports for oil, coal, natural gas, and uranium. Japan is one of the largest users of energy – only the United States, China, and the Russian Federation had a higher total usage in 1995.

Japan emitted 1,127 million metric tons of carbon dioxide (307 million metric tons of carbon) in 1995, an increase from 907 million metric tons of carbon dioxide (247 million metric tons of carbon) emitted in 1980.[83] As part of the Kyoto Protocol, Japan agreed to reduce greenhouse gas emissions to 94% of their 1990 levels by about 2010.

Japan's electric power industry is dominated by ten regional companies, which provide some 77% of the electricity in Japan. Table 13 describes the organization of the electric power industry.

Table 13: Structure of Japanese Electric Power Industry

Type of Organization	% of Capacity	Description
General Suppliers		
Regional electric power companies (10)	76.8	Investor-owned; monopolized service areas
Wholesale Suppliers		
Electric Power Development Company, Ltd.	5.5	Initially hydro power development; currently developing coal and nuclear plants. May become involved with wind power projects.
Japan Atomic Power Company	1.2	Nuclear power development
Public enterprises (34)	1.1	Owned and operated by local governments
Joint venture companies (20)	5.0	Partnerships between regional power companies and large consumers (iron, steel, etc.)
Other		
Industrial electricity production for internal consumption ("auto-producers")	10.4	Electricity generated and consumed on-site
Special electricity suppliers	0.0	New category created in 1995, electricity sold directly to consumers

Data for 1996. Source: JEPIC 1997b.

Japan's electric capacity through March 1997 was 233,737 MW, and total electricity production in 1996 was 1,009 terawatt-hours. Thermal power plants produce roughly

[82] MITI/ANRE 1997, page 5.
[83] World Bank 1998, Table 3.8.

60% of Japan's electricity, nuclear 30%, and hydro 9%. Table 14 and Table 15 show the installed electric capacity and electricity generation by energy source. Between 1986 and 1996, electricity generation grew by 50%, a growth rate of about 4 percent per year.[84] The rate of increase appears to be slowing, with generation in 1996 about 1.9% higher than generation in 1995. Annual average electricity growth through 2006 is expected to average 1.9% per year.[85]

Table 14: Electric Generating Capacity – Japan

Type	Electric Capacity (MW Installed)	% of Total
Thermal	146,074	62.5
Hydro	44,407	19.0
Nuclear	42,712	18.3
Geothermal	530	0.2
Fuel Cell	12	< 0.1
Photovoltaic	1.4	< 0.1
Wind	1.1 *	<0.1
Total	233,737	100.0

Data through March 31, 1997. Source: JEPIC 1997b, Table 2.
* Note that other sources (e.g., NEDO 1997) list 14 MW at the end of 1996, and mid-1998 capacity is estimated at 25 MW (Ushiyama 1998a).

Table 15: Electricity Generation - Japan

Type	Electricity Generation (Terawatt-hours)	% of Total
Thermal (incl. Geothermal)	618	61.2
Nuclear	302	29.9
Hydro	89	8.8

Data for 1996. Source: JEPIC 1997b, Table 8.

Japanese electricity rates are divided into two categories: "lighting," which includes residential customers, and "power," which consists of industrial and commercial customers. In 1996, lighting electricity rates were 24.16 yen per kWh and power electricity rates were 16.56 yen per kWh. The average rate charged was 18.81 yen, or 11 ¢, per kWh.[86] Note that these are the costs to the customer, not the cost to generate electricity. Thus, they include transmission and distribution costs, for example.

Prior to 1992, only electric utilities and a few electricity wholesalers were able to sell "surplus" electricity.[87] That is, while other entities could produce electricity for their own use, they were not allowed to sell any of their surplus electricity. In 1992, the Ministry of International Trade and Industry instructed the ten electric utilities to begin a

[84] FEPC 1997a, page 5.
[85] JEPIC 1997a, page 12 and JEPIC 1997b, Table 30.
[86] JEPIC 1997b, Table 24. Exchange rate used is the purchasing power parity rate, which in 1996 was 171 yen to the dollar.
[87] Nakada 1995.

program to purchase such “surplus” electricity generated from alternative sources of energy. Electricity contracts for purchase of wind electricity were reportedly 15 to 20 yen per kWh, roughly equal to the average cost of delivered electricity noted above for Japan in 1996.[88] This is a voluntary program on the part of the utilities, however, and does not necessarily include long-term contracts.[89] In addition, at least one utility has changed their program so that it would purchase electricity at these rates only from alternative energy projects that consumed more than half of their energy on-site or those that were for non-commercial purposes (e.g., education or research). A major change is a 1995 law that opened up the electricity generating business to independent power producers, opening up the market for generation and sale of electricity.

Plutonium Program

Japan has the world’s third largest nuclear power capacity, after the United States and France. At the end of 1996, 52 reactors with an installed capacity of almost 43,000 MW produced 302 terawatt-hours of electricity, about 30% of Japanese electricity. Tokai I, Japan’s first nuclear reactor, which began operating in 1966, was shut down for decommissioning in March 1998. Two new reactors, the Kashiwazaki Kariwa 7 advanced boiling water reactor and the Genkai 4 pressurized water reactor, began operating in July 1997.[90] As of June mid-1998, the only nuclear power plant under construction was the 825 MW Onagawa III boiling water reactor, with a scheduled start of operation in January 2002.[91]

In June 1994, the Japan Atomic Energy Commission issued its Long Term Program for Research, Development, and Utilization of Nuclear Energy, calling for nuclear power capacity of about 70,000 MW, producing 480 TWh of electricity per year, by 2010.[92] The 2010 goals were reaffirmed in a 1998 update, though the plan also states that fewer nuclear power plants could be built and the capacity factor of operating plants could be raised so that the 480 TWh figure is reached.[93] Moreover, plans call for 100,000 MW of nuclear power by the year 2030 – more than double the nuclear power capacity operational in 1998.[94]

Japan began its ambitious plutonium program, centered around fast breeder reactors and advanced thermal reactors, in the 1970s. The only reprocessing plant to operate in Japan, Tokai, is a pilot plant facility which opened in 1977. The commercial-scale Rokkasho plant, with a planned capacity of 800 tons, is under construction, and is scheduled to begin operation sometime early in the next century. In the face of a lack of domestic capability, Japan has relied primarily on contracts with Cogema in France (which operates reprocessing plants at La Hague) and British Nuclear Fuels, Limited in the U.K.

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[88] IEA 1996, page 102.
[89] Iida 1999. Long-term contracts are helpful in obtaining favorable financing arrangements and lowering the cost of electricity over the lifetime of the plant (the “levelized” cost of electricity).
[90] Japan Electric Power Survey Committee 1998, page 8 and FEPC 1997a, page 13.
[91] FEPC 1997a, page 13 and CNIC 1998 page 3.
[92] JEPIC 1997b, Tables 31 and 32.
[93] MITI/ANRE 1998, Executive Summary and CNIC 1998, page 3.
[94] MITI/ANRE 1997, pages 38-39.

(which operates the Thermal Oxide Reprocessing Plant at Sellafield) for its plutonium separation. The transport of plutonium from Europe back to Japan that these contracts have involved evoked international criticism during the Akatsuki-maru shipment of 1.5 metric tons of plutonium from France to Japan in the early 1990s.[95]

Separated plutonium, fabricated into mixed-oxide (MOX) fuel at two facilities at Tokai, has been used primarily in three experimental reactors. The Joyo fast breeder reactor, which was commissioned in 1977, began operating with MOX in 1979. The Monju fast breeder reactor (280 MW), which achieved criticality in April 1994, was fueled with MOX until a sodium leak closed it down in December 1995.[96] The Fugen reactor, a prototype advanced thermal reactor (ATR), opened in 1979 and is expected to be decommissioned in the near future.[97] In August 1995, Japan cancelled the demonstration Advanced Thermal Reactor (ATR), which was also supposed to use MOX fuel.[98]

Originally, Japanese plans foresaw that fast breeder reactors and ATRs would consume separated plutonium.[99] However, in the 1980s, Japan began considering MOX use in light water reactors. Two small demonstration projects have been carried out in light water reactors: in 1986 two fuel assemblies were loaded at the Tsuruga 1 boiling water reactor, and beginning in 1988, four MOX fuel assemblies were loaded at the Mihama pressurized water reactor.[100]

Japan describes the nuclear program in three phases:[101]

- Phase I: Nuclear energy generated using uranium fuel
- Phase II: Establishment of "core nuclear fuel cycle projects," such as enrichment and reprocessing, on a commercial scale in Japan and use of plutonium in MOX fuel in light water reactors
- Phase III: Further development based on plutonium technologies, notably fast breeder reactors.

A summary of the key elements of Japan's plutonium plan are shown in Table 16.

[95] CNIC 1997, page 67.
[96] Albright, Berkhout, and Walker 1997, pages 202-3.
[97] CNIC 1997, page 69. The Advanced Thermal Reactor (ATR) is a heavy water moderated, light water cooled reactor capable of being fuelled by MOX with low (2%) plutonium content.
[98] The demonstration ATR was a 600 MWe reactor planned at Ohma, Aomori.
[99] Albright, Berkhout, and Walker 1997, pages 219-221.
[100] WISE 1994, page 45.
[101] MITI/ANRE 1997, page 42.

Table 16: Key Elements that have been proposed for Japanese Plutonium Program

Elements of Program	Official Target Year
MOX use in light-water reactors	10 reactors in 2000
Demonstration Advanced Thermal Reactor	Start operation early 2000's
Demonstration Fast Breeder Reactor	Start construction early 2000's
Rokkasho reprocessing plant	800 ton capacity plant early 2000's
Nuclear power capacity	70 GWe in 2010; 100 GWe in 2030
Fast Breeder Reactor	Commercial around 2030

Source: Citizens' Nuclear Information Center (CNIC) 1997, page 68.

With operation of the Rokkasho uranium enrichment plant (operational since 1992), initiation of construction of the Rokkasho reprocessing facility, and application in May 1998 by Kansai Electric Power Company for a safety review to allow use of mixed-oxide fuel (MOX) in its Takahama 4 pressurized water reactor, Japan is pressing forward with Phase II of its nuclear program.

However, numerous setbacks to the plutonium program have occurred over the past few years. Under current plans, existing reactors would be re-licensed to use MOX fuel.[102] Due to delays, the Japanese Federation of Electric Power Companies of Japan stated that it is planning to have four reactors using MOX fuel in 2000, rather than the ten announced in 1994.[103] Table 17 shows the plans for MOX use in light water reactors announced in February 1997 by the Electric Companies. Given the problems and delays in the program, use of 70 to 75 metric tons of plutonium in MOX fuel by 2010 is highly unlikely.[104] Even with the Electric Companies' optimistic schedule for introducing MOX fuel, we estimate plutonium use of less than 40 metric tons.[105]

Table 17: Japanese MOX Utilization Plan

Year	1999	2000	Shortly after 2000	2010
# of reactors	2	4	9	16-18

Source: FEPC 1997b.

Cost increases have also plagued the Japanese plutonium program. For example, construction costs for the Rokkasho reprocessing plant are more than double the original estimates – estimates of total cost are now 1,880 billion yen, or about $11 billion.[106] If completed, the plant will have costs much higher than reprocessing facilities in Europe.

[102] MOX fuel fabrication would initially take place in Europe, according to current plans. However, some of the plutonium has been separated for more than five years and would likely require further chemical processing to remove americium-241, which builds up in commercially-separated plutonium due to the decay of plutonium-241.
[103] FEPC 1998 and CNIC 1997, page 68.
[104] CNIC 1997, page 68, cites the plutonium amounts from the 1994 Long Term Program for Research, Development, and Utilization of Nuclear Energy.
[105] Assuming plutonium use of 0.3 tons per 1,000 MWe reactor per year for 1/3 MOX loading (CNIC 1997, page 160). Our estimate assumes all reactors planned for MOX use are 1,000 MWe.
[106] Takagi 1997. Conversion using the 1996 purchasing power exchange rate of 171 yen to the dollar. The dollar estimate would be even higher using actual currency exchange rates.

Since Japan continues to separate plutonium from irradiated fuel but has not yet begun to implement its program of using this plutonium in commercial reactors, the plutonium stockpile has been increasing. Japanese stocks at the end of 1996 (as reported to the International Atomic Energy Agency) totaled 20.1 metric tons.[107] The Citizens' Nuclear Information Center (CNIC) in Tokyo lists Japanese separated plutonium to be 22.9 metric tons at the end of 1997, with 19 tons at facilities in Europe.[108] Continued reprocessing is increasing this stockpile, and some analysts predict that given delays in the MOX program and serious problems with the fast breeder reactor program, Japan will have more separated plutonium in 2010 than it does now.[109] The accumulation of plutonium has evoked serious concerns. For example, North Korea has officially complained to the International Atomic Energy Agency in 1991 about Japan's plutonium program.[110]

Japan's Phase III plans are facing even greater difficulties. A serious accident at the Monju breeder reactor on December 8, 1995 called into question the safety of breeder reactor technology and has essentially halted the Japanese program. The accident, which leaked 2-3 cubic meters of sodium from a secondary cooling loop, resulted in a damaging fire when the sodium reacted with air. Investigations revealed attempts to cover-up of the seriousness of the accident by the government-owned Power Reactor and Nuclear Fuel Development Corporation (PNC, the owner and operator of Monju).[111] One of the investigators committed suicide the day after it was revealed that PNC Tokyo headquarters was directly involved in the attempts at a cover-up. The accident at the Monju reactor once more revealed design and economic weaknesses in breeder reactor technology.

Following the Monju accident, the governors of Fukushima, Niigata, and Fukui (prefectures that contain 60% of Japanese nuclear power reactors) asked the Prime Minister to thoroughly review Japan's nuclear policy, in particular the plutonium program.[112] CNIC observed that

> it is highly unlikely that the restart of Monju will get approved in the foreseeable future by the prefectural government and people of Fukui. Without the approval, Monju can never be started and without operation of Monju Japan will not be able to take any further step in its FBR [fast breeder reactor] program. (CNIC 1997, page 70)

In August 1996, voters rejected construction of a proposed nuclear power plant in their community in Japan's first such referendum (at Maki-machi in Niigata Prefecture).[113] Other accidents have also occurred in Japan's nuclear program, one a March 1997 fire

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[107] Press release from Japan Science and Technology Agency, December 5, 1997. Japan also reported 48.8 tons of unseparated plutonium in irradiated nuclear fuel. Official information is submitted to the International Atomic Energy Agency and published in Information Circular INFCIRC/549/Add.1 (www. iaea.or.at/worldatom/infcircs/98index.html).
[108] CNIC 1998, page 5.
[109] CNIC 1997, pages 76-79.
[110] Leventhal 1992.
[111] CNIC 1996, "Plutonium Policy Stalled."
[112] CNIC 1997, pages 69-71.
[113] CNIC 1997, page 80.

leading to an explosion at the Low-Level Radioactive Waste Bitumenization Facility of the Tokai Reprocessing Plant, and another a tritium leak in April 1997 at the Fugen reactor, that have increased public distrust.[114]

Increasing public opposition to nuclear power, accidents and disclosures of official cover-up, and an eroding technical justification create an opportune time for re-evaluation of Japan's energy programs.

Japan's Wind Energy Program

Compared to its plutonium program, wind energy investment in Japan has been negligible. Installed wind capacity in Japan through mid-1998 was a mere 25 MW.[115] The Japanese government's projections for total wind capacity in Japan are also very modest, to say the least. The 1998 "Long-term Outlook of Japanese Energy Supply and Demand" included a target of 300 MW by 2010.[116] These targets are increased from the December 1994 "Basic Guideline for New Energy Introduction" (which had a goal of 150 MW of wind power in 2010) though they are still relatively low.[117]

Complex terrain, such as steep and mountainous areas, has been cited as an obstacle to development of wind energy in Japan.[118] Gusty and turbulent winds in these areas increase the mechanical stress on wind turbines, which may reducing life of components such as turbine blades. Further, construction in such terrain is more costly and difficult than in flatter areas. However, Japan has good wind resources in the north (Hokkaido and Tohuku), in island areas in the south (Okinawa and Kyushu), and the coastal regions of Honshu.[119]

Japan has had a research and development program in wind energy since 1981.[120] The New Energy and Industrial Technology Development Organization (NEDO) carries out the bulk of this program. The NEDO budget was about 1 billion yen in 1997, with the "New Sunshine Project" accounting for about half of the budget and the "Field Test Program" the other half.[121] The 1998 budget was increased to 1.53 billion yen.[122] Efforts under the "New Sunshine Project" have included publication of a wind atlas for Japan, development of a small wind farm on Miyako Island in Okinawa, and design and testing of a 500 kW wind turbine at Tappi Misaki in Aomori Prefecture, the northern part of Honshu.

Results from the Japanese wind atlas, published in 1995, are summarized in Table 18. Sites with wind speeds of over 5 meters per second at 30 meters height were included.

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[114] CNIC 1997, page 70.
[115] Ushiyama 1998a.
[116] Ushiyama 1998a.
[117] NEDO 1997.
[118] IEA 1998.
[119] Ushiyama 1998b.
[120] NEDO 1997.
[121] IEA 1997
[122] Matsuyama 1999.

The three different scenarios represent different assumptions about land use restrictions. Mid-range estimates yield a land-based wind energy potential on the order of a few percent of total Japanese electricity generation.

Table 18: Land-based Wind Energy Potential in Japan

Scenario	Suitable Land Area, km^2 *(% of Japanese land area)*	Potential Number of Turbines	Potential Capacity, MW	Potential Generation, TWh *(% of total 1996 generation in Japan)*
1	23,280 *(6.4)*	125,519 – 465,278	(not given)	(not given)
2	3,599 *(1)*	18,430 – 70,481	9,220 – 35,240	8.9 – 34 *(0.88 – 3.4)*
3	758 *(0.2)*	2,792 – 13,743	1,440 – 6,870	1.3 – 6.5 *(0.13 – 0.65)*

Notes:
500 kW turbines assumed.
The low value for each scenario corresponds to turbine spacing of 10 diameters by 10 diameters; the high value for each scenario represents spacing of 10 diameters by 3 diameters.
The estimates of potential generation appear to be rather low since they imply a capacity factor of about 11%.
Sources: IEA 1996. Percent of total 1996 generation calculated using JEPIC 1997b, Table 8.

The project at Miyako (consisting of 5 turbines with a total capacity of 1.7 MW) is involved in developing control technologies for frequency and voltage fluctuations and studying integration of wind power with small electricity grids. The 500 kW turbine was installed at the end of 1996, and research has focused on pitch drive systems (that is, control of the angle of the turbine blades) and studies of stress on turbine blades in turbulent winds.

The Japanese government has several incentive programs to promote use of wind power, in addition to its research program. NEDO's "Wind Power Development Field Test Program," began in 1995, provides eligible projects with a 100% subsidy for detailed wind studies, a 50% subsidy for system design, and a 50% construction subsidies for the first turbine installed.[123] Data from each of the phases for these projects are collected by NEDO to promote other wind projects. Another program, "Subsidy for Power Generation for Regional Development," is managed by the Ministry of International Trade and Industry, and provides subsidies of up to 30% of the cost of projects contributing to regional energy development. There are also tax incentives that allow a 7% credit on equipment costs or special depreciation schedules for wind projects. Another program, managed by the National Land Agency and the Ministry of Agriculture, Forestry, and Fisheries, subsidizes up to 1/3 of the cost of wind projects for distant farming and fishing villages.

[123] Details on the NEDO program from NEDO 1997 and Kajita 1999.

As noted above, wind power capacity in mid-1998 was only 25 MW.[124] Tappi Wind Park (also the site of NEDO's 500 kW test turbine) is Japan's first utility-scale wind farm. When it began operation in 1991, it initially consisted of 5 turbines. In 1995, 5 more turbines were added for a total capacity of about 3 MW. There has been a recent increase in activity, however, partly encouraged by the changes to the electricity sector noted above. In 1997, EcoPower Company, Limited, a Tokyo-based company independent power producer, announced plans to develop 60 MW of power over three years.[125] Other power producers, such as Electric Power Development Company, a state-owned utility, and Tomen Corporation, a multinational corporation with a long history of wind projects in Europe and the U.S., may also be investigating the possibility of developing wind parks in Japan.

Offshore Wind Energy for Japan

Development of offshore wind energy in Japan would likely address many of the problems facing development of wind power on land. Constraints imposed by difficult terrain and high population density would be eliminated. Better wind conditions, including higher wind speeds and less turbulence, are likely. Further, the economics of offshore wind farms will likely be equal to or even better than many onshore wind farms, given larger machines, better winds, and lower site acquisition costs.

The total amount of electricity available from offshore wind in Japan is at present quite uncertain. Systematic evaluation of the potential of this resource has only just begun. One study used wind data from 31 lighthouses around Japan to estimate the offshore wind potential.[126] Three scenarios were chosen, representing a range of turbine spacing diameters and distance from shore. The study assumed that 80% of the coastline was free from limitations such as ports and shipping lanes. Some results are shown in Table 19.

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[124] Domestic development was slow despite the fact that one Japanese manufacturer was a leader in the 1980s and early 90s, supplying some 800 turbines to the US and the UK (Nakada 1995).
[125] Dahl 1997a.
[126] Nagai, Ushiyama, and Ueno 1997.

Table 19: Estimates of Japanese Offshore Wind Resources

Maximum Distance from Coast, kilometers	Area Available, square kilometers	Turbine Spacing	Number of Turbines	Annual Average Electricity Generation, Terawatt-hours
1	6,500	10 diameters by 3 diameters	136,500	94
3	19,600	10 diameters by 3 diameters	409,700	280

Source: Nagai, Ushiyama, and Ueno 1997.
Note: For the 10 diameters by 3 diameters case, wind turbines would be spaced 10 diameters apart along the direction of the prevalent wind, and 3 diameters apart perpendicular to the direction of the prevalent wind. This spacing is more dense than assumed in other studies of offshore resources. Spacing of ten diameters by ten diameters is a density more commonly cited in the literature. A ten by ten spacing would reduce the electricity generation to about one-third of that estimated for a ten by three spacing.

Depending on the assumptions used, Japan's offshore wind energy potential ranged from about 90 to 280 TWh per year, or 9 to 28 percent of Japan's total 1996 electricity generation. These estimates are much higher than estimates of Japan's land-based wind resource (see Table 18). Moreover, the available area and electricity potential would be far greater if areas farther from shore (up to 40 kilometers, such as in Denmark) were considered for shallow areas (10 to 15 meters water depth based on current technology). In the long term, it may be possible to install wind turbines in deeper waters, either on less costly foundations or on floating platforms.

Given the significant offshore potential, more thorough studies should be carried out. Assumptions in the preliminary estimates, such as the percent of coastal areas free from incompatible uses and appropriate turbine spacing should be examined more closely and data from more than just 31 sites should be gathered. The key issue that needs to be evaluated, in terms of economics, is the importance of water depth. Detailed maps of offshore wind power potential should be generated and overlaid onto maps of water depth. It will also be necessary to examine daily and seasonal variation in the offshore wind energy resource and the extent to which it corresponds to energy demand patterns.

Comparison: Wind Energy Versus Plutonium

Here we compare the costs and electricity generation potential of using plutonium as a fuel with those of wind development in Japan. The purpose is to examine long-term energy choices and how they affect short- and medium-term decisions. We compare plutonium in breeder reactors to wind energy, both of which have been promoted as very long-term solutions. For the short-term and medium-term, we compare electricity from MOX fuel in light water reactors to wind energy. Both of these options could possibly be implemented within the next couple of years.

Japan has spent enormous ratepayer and taxpayer resources on its plutonium program on the premise that it is the only long-term route to energy independence. Whatever the past rationale, continued expenditures of public resources on this program can no longer be justified in view of the large potential of wind energy. The current economic question regarding wind is not whether it is economical under all circumstances, but whether public investment in it on a large-scale is justified relative to plutonium, which is clearly uneconomical. Our case study is designed to address this crucial question, especially in light of the need to reduce greenhouse gas emissions.

Near-term: Offshore wind vs. MOX

Japan has proposed using MOX fuel in light water reactors beginning as early as 1999, an option that is more expensive than the uranium fuel currently used in Japan's nuclear power plants. The justification for higher costs is that MOX use will help develop technologies that are key to breeder reactors, an energy system for the long-term. (We analyze the long-term prospects for breeder reactor technology in the next section). Here, we consider an alternative: offshore wind power. Wind power, a renewable resource, has also been proposed as a basis for a long-term energy system.

Japan has a specific schedule for conversion of some of its reactors to MOX fuel. The current plan (see Table 17), is to use approximately 5 tons of plutonium per year by the year 2010 in 16 to 18 reactors.[127] This appears optimistic in view of the problems that plague Japan's plutonium program. Annual electricity generation from MOX would amount to about 39 TWhe per year by the year 2010.

We have constructed a program for wind energy for Japan that would result in almost the same annual generation of electricity by the year 2010. The amount of wind capacity installed each year would increase gradually from 300 MW in the year 2000 to 2,500 MW in the year 2010, as shown in Table 20. This plan is quite feasible and is comparable to plans of the European and US wind energy associations.[128] The total wind energy resources that it would tap are well within the available resources (offshore and onshore, though mainly offshore). The total installed capacity by the year 2010 would be about one-third of the potential estimated for coastal regions within 1 kilometer of the coast in the Nagai, Ushiyama, and Ueno study.

[127] For MOX use in 17 reactors. We assume 1,000 MW reactors, using 0.3 metric tons of plutonium per year (CNIC 1997, page 160).

[128] The American Wind Energy Association has proposed 30,000 MW of capacity in the U.S. by the year 2010 (AWEA 1998b) and the European Wind Energy Association has called for 100,000 MW of wind in Europe by 2020 (EWEA 1998). Greenpeace U.K. has published a study of 12,000 MW of wind capacity by 2010 for the U.K. (Border 1998).

Table 20: Offshore Wind Installation in Japan to Replace Proposed MOX Use through 2010

Year	New MW Installed	Total MW	TWh per Year
2000	300	300	0.8
2001	500	800	2.2
2002	500	1,300	3.6
2003	500	1,800	5.0
2004	500	2,300	6.4
2005	1,000	3,300	9.3
2006	1,000	4,300	12.1
2007	1,500	5,800	16.3
2008	2,000	7,800	21.9
2009	2,000	9,800	27.5
2010	2,500	12,300	34.5

Introduction of wind power based on proposal in Border 1998 to produce 10% of the U.K.'s electricity from wind. Capacity factor of 0.32 assumed.

For turbine spacing of 10 rotor diameters by 10 rotor diameters (a density of 3.1 MW per square kilometer), the 12,300 MW of offshore wind power would be distributed over an area of roughly 4,000 square kilometers.

Costs for offshore wind and MOX fuel, shown in 1997 dollars, are presented Table 21.

Table 21: Comparison of Wind and MOX Costs

Cost Component	**Offshore Wind**	**MOX fuel**
Capital cost	4.2 ¢ / kWh	3.8 ¢ / kWh
MOX Fuel cost (exclusive of reprocessing)	n/a	0.9 ¢ / kWh
Reprocessing cost	n/a	0.7 ¢ / kWh
Operating and maintenance costs	1.2 ¢ / kWh	1.5 ¢ / kWh
Other		
Nuclear waste disposal costs for MOX spent fuel	n/a	0.2 ¢ / kWh
Decommissioning costs	0.14 ¢ / kWh	0.1 ¢ / kWh
Total	**5.54 ¢ / kWh**	**7.2 ¢ / kWh**

Notes:
Wind costs
Data from Kühn et al. 1998. Wind resource assumed to be 8.4 m/s annual average wind speed.
Capital costs are $1,360 per kW. Capacity factor = 30%, capital recovery factor = 8%. Decommissioning costs based on 10% of initial capital cost.
Conversion: $1 US = 0.9 ECU.
MOX costs
Except where noted, costs are taken from Cohn 1997, page 155. Costs in sources are given in 1992 or 1995 dollars, but for the sake of this comparison, we assume that the costs in 1997 dollars would be the same (that is, we have not adjusted for inflation here).
Power plant: $2,500 per kW. Capacity factor 75%. Interest and depreciation = 10%.
Fuel costs based on LEU fuel from Cohn 1997, plus incremental MOX cost from NAS 1995, page 301.
Reprocessing costs based on $2,100 per kg heavy metal (NAS-NRC 1996), 32% thermal efficiency, and burnup of 40,000 MWdth / metric ton.
Waste disposal costs based on Makhijani and Saleska 1996, page 100 ($330,000 per metric ton of spent fuel, burnup of 40,000 MWdth per metric ton, and 32% thermal efficiency), plus incremental MOX spent fuel management cost of 0.1 cent per kWhe.

For both offshore wind and MOX, capital costs make up the largest component of cost. The sum of capital costs and operation and maintenance costs in both cases are similar. The MOX option, unlike the offshore wind option, incurs costs for fuel, including reprocessing and fabrication. While the decommissioning costs shown in Table 21 are slightly higher for offshore wind than nuclear power plants, the reverse is likely to be true in practice. Further, the comparison is not quite equal because the wind decommissioning costs include removal, recycling, and disposal of the entire structure (including the turbine base), whereas decommissioning of nuclear power plants may leave long-lived radioactive contaminants in-place and will likely require land to be removed from productive use for a long period of time.

The costs for the MOX scenario are likely understated in Table 21 for a number of reasons. MOX fuel complicates reactor control issues and modifications may be necessary.[129] We do not include reactor re-licensing costs, cost of lost electricity production during reactor modifications, and costs due to unexpected delays. We assume no post-operation capital cost additions due to a change in fuel from uranium to plutonium (partial or full MOX core). Also, the high-end cost estimate for nuclear power plant decommissioning is four to ten times higher than we have used here.[130] Further, given Japan's scarcity of land, the costs of a repository for high-level nuclear reprocessing waste are likely to be higher than those shown here, which are based on US cost estimates. A more realistic cost estimate for MOX fuel use in light water reactors in Japan may be 8 cents per kWh, possibly more.

Moreover, MOX fuel has significant disadvantages not shown in Table 21. Reprocessing, necessary to separate plutonium from the irradiated fuel, poses significant environmental and safety risks.[131] Discharge of radioactive wastes into the sea may damage fisheries, as is the case in the Irish and North Seas. Further, separation of plutonium, which can be used to make nuclear weapons, undermines non-proliferation efforts. Civilian reprocessing is currently by far the most important contributor to growth in nuclear weapons-usable materials in the world.[132] Additionally, the higher proportion of plutonium in reactors with MOX would increase the health and environmental impacts of a serious accident. These costs are not easily quantifiable, but they are nonetheless quite real.

For the offshore wind power scenario, the issue of intermittent power needs to be considered. As discussed above, the daily and seasonal variation in the offshore wind energy resource and the extent to which it corresponds to energy demand patterns affect the value of wind electricity. With a large, diverse grid system an upper limit for wind of 25 to 45 percent of system energy could likely be incorporated with the need for major investments in upgrading transmission and distribution infrastructure or energy storage.[133] The electricity grid on the coast at the point of connection with the offshore wind farm may need to be upgraded; this will depend on site-specific conditions. The estimates in Table 21 do not include costs for investments in energy storage or major investments in upgrading transmission and distribution infrastructure. For the near- and medium-term, when offshore wind energy is highly unlikely even to approach 25%, such costs should not be significant. Hence, the intermittent nature of the wind does not materially affect our near-term comparison.

The capital costs for offshore wind power in Table 21 assume turbines that are larger than those commercially available in 1998 and that are optimized for offshore conditions. We calculate that an increase in capital costs to roughly $1,850 per kW would make the cost of wind electricity equal to the most optimistic MOX case (about 7 ¢ per kWh). This cost is 36% greater than the Opti-OWECS study. The costs estimated by the Danish Wind

[129] Makhijani 1997.
[130] Cohn 1997, pages 157-8.
[131] Sachs 1996.
[132] Albright, Berkhout, and Walker 1997, chapter 14.
[133] Grubb and Meyer in Johansson, et al. 1993, page 185.

Turbine Manufacturers Association for current technology was $1,700 per kW in 1998 in currency terms.[134]

As noted above, the costs of wind power have come down dramatically and most analysts estimate a continued decrease. For offshore wind turbines, lower turbulence would reduce wear on components. Further, foundations, towers, nacelle shells, and main shafts in the turbines can be designed for fifty year lifetimes, with shorter-lived components replaced after twenty or twenty-five years.[135] The increase in cost to design for longer lifetimes would be more than offset by a doubling of their period of use, resulting in a significant decrease in the cost of electricity.

Even using the understated MOX costs in Table 21, MOX is 22% more expensive than the projected cost of offshore wind electricity in the next 5 to 10 years. The cost of the program (in terms of electricity costs) would be hundreds of millions of dollars or even billions of dollars lower than that for MOX fuel.[136] Our analysis shows that not only is offshore wind energy development capable of replacing Japan's plans for use of MOX fuel through at least the year 2010, but that there are no short- or medium-term economic benefits of MOX fuel use relative to wind. Moreover, wind energy is far superior on environmental, safety, and non-proliferation grounds. Thus, there is no reasonable short- or medium-term basis for proceeding with the MOX program in Japan. The long-term rationale is provided by the argument that the MOX program in light water reactors will be a transition to breeder reactors. We turn to this comparison next.

Long-term: Offshore wind vs. Breeder reactors

Tens of billions of dollars have been spent on research, development, and demonstration of breeder reactor technology, yet it has not reached the stage of even moderately reliable power or breeding of plutonium.[137] These efforts, however, have failed to produce a viable program in any country. One dramatic example of this massive investment is the Superphénix – once the world's largest fast breeder reactor.

On June 19, 1997, the operator of Superphénix announced that the facility, located in France, would be permanently shut down .[138] Original plans did not envision shutdown of the reactor until the year 2015. The 1,200 MW reactor represented almost half of the world's breeder reactor capacity (though in 1994 it was reconfigured to operate as a net consumer, rather than producer, of plutonium). Superphénix operated only 278 days of full-power equivalent between 1986 and 1997.[139] Total costs of the Superphénix project

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[134] DWTMA 1998, "Economics of Offshore Wind Energy." Equivalent to $1,400 per kW using purchasing power parity conversion of 8.53 DKK per US dollar (OECD 1998).
[135] DWTMA 1998, "Economics of Offshore Wind Energy."
[136] Using a cost difference of 1.6 cents per kWh, the cumulative savings due to wind energy relative to MOX would be about $2.5 billion. However, since this cost difference is based on anticipated short-term cost reductions in offshore wind, the actual cost savings would be somewhat lower than this figure.
[137] Makhijani 1996.
[138] EdF 1998. The operator of the project is Nuclear European Society for Fast Breeders, which consisted of French, Italian, German, Belgian, and Dutch partners.
[139] WISE 1997.

were estimated at 60 billion francs (1994 francs), or about $9.1 billion, in 1996 (before the shut-down was announced).[140] The decommissioning and post-operation costs of Superphénix alone, estimated at 9.5 billion francs (about $1.4 billion) would be enough to pay the capital costs for about 825 MW of offshore wind power capacity.[141]

Costs for future breeder reactors are speculative. Leventhal and Dolley noted that Japanese government officials estimated a 500 to 600 billion yen (1993 yen) cost for a demonstration fast breeder reactor.[142] Assuming a 600 MWe reactor, specific capital costs for this reactor would be about $4,500 to $5,400 per kW (1993 dollars).[143] Costs for another key component of the fast breeder reactor option, a reprocessing plant for MOX fuel, are also uncertain. A 1988 Department of Energy report assumed that capital costs for such a plant would be 40% higher than a low-enriched uranium reprocessing plant, due greater worker safety and environmental concerns.[144]

With capital costs of $5,000 per kW and MOX reprocessing costs 40% greater than low-enriched uranium reprocessing costs, the cost for electricity from fast breeder reactor would be 11.3 ¢ per kWh – about double the Opti-OWECS study's projected costs for offshore wind energy (for sites with a conservative 8.4 meters per second wind speed). Table 22 shows a breakdown of estimated electricity costs from breeder reactors. As noted above, costs for breeder reactor technology are speculative and there is no trend indicating decreasing breeder reactor costs. Our cost estimates are based on past performance and the present state of technology. The main components of the costs in Table 22 are highly optimistic. The actual costs may be as high as 15 ¢ per kWh, given the historically low capacity factor of large-scale breeder reactors and likelihood of larger decommissioning costs.

Table 22: Estimated Costs of Electricity from Breeder Reactors

Power plant capital	Fuel (excluding reprocessing)	Reprocessing	O&M	High-level waste disposal	Decommission-ing	Total
7.6	0.9	1.0	1.5	0.2	0.1	11.3

All costs in ¢ per kWh.
Power plant capital costs based on estimates cited in text for a 600 MWe demonstration fast breeder reactor (about $5,000 per kW), 30 year life, 10% interest and depreciation, and 75% capacity factor.
Reprocessing costs estimated to be 1.4 times the cost of a low-enriched uranium reprocessing plant.
Other costs taken from Table 21.

If offshore wind is to be properly compared with a baseload power plants, such as nuclear reactors and fossil fuel plants, energy storage systems need to be considered. A large-scale energy system powered largely by sources such as solar and wind must use

[140] French Accounting Office 1996. Costs are through the year 2000, listed in constant 1994 francs. OECD purchasing power parity conversion of 6.6 francs per dollar (average of 1993 and 1995) (OECD 1998).
[141] EdF 1998. We assume prices cited by Danish Wind Turbine Manufacturer's Association, $1,700 per kW in 1998.
[142] Personal communication from Japanese government official cited in Leventhal and Dolley 1994, page 5 and footnote 11.
[143] OECD purchasing power parity conversion of 184 yen per dollar for 1993 (OECD 1998).
[144] The 40% figure is cited in Leventhal and Dolley 1994, page 8.

technologies that enable these intermittent resources to provide energy when it is required, not just when the sun is shining or the wind is blowing. Options such as energy storage and hydrogen fuel are discussed below. Significant investments will be required for a large-scale wind energy systems – where wind energy provides greater than about 25 to 45 percent of the electricity supply. The most straightforward option is to incorporate energy storage technologies, for example in batteries or as hydrogen, that allow electricity production to better match the pattern of energy demand.

The storage needs could straightforwardly be met by large arrays of batteries. Capital costs for an energy system with battery energy storage would be expected to be on the order of 25 to 30 percent more expensive than without battery energy storage.[145] While significant, wind energy costs would still remain lower than the costs of breeder reactors. Other storage technologies, particularly compressed air energy storage, may be more attractive than battery storage on environmental grounds.

An environmentally-sound long-term wind energy system would likely require improvements in battery technology, commercialization of other large-scale storage technologies, or a transition to a hydrogen economy. If achieved, wind could supply most energy requirements and be fully comparable to plutonium. The technical development required is likely to be achieved in the next couple of decades. We shall briefly discuss the hydrogen energy case, which is also germane to an energy self-sufficiency goal because fuel cells (which run on hydrogen fuel) are a likely source of electricity for on-board electric power supply for motor vehicles.

Hydrogen can be produced by using electricity to electrolyze water. The electricity may come from any source, such as a wind turbine generator or a nuclear reactor. Hydrogen would create a link between transportation and electricity sectors that would dramatically change patterns of energy use. Use of hydrogen as a fuel may result in significant benefits compared to current energy use in the transportation sector. Hydrogen is a clean energy resource, and use in fuel cells to power vehicles would result in no air pollution or emission of greenhouse gases at the point of use.[146] Further, devices such as fuel cells are highly efficient – 2 to 3 times more efficient than internal combustion engines used in passenger vehicles today. Further, for use in vehicles, hydrogen storage may be more advantageous than batteries which are usually quite heavy and not as efficient overall.

Let us examine a scenario proposed by one set of researchers: 750 MW of wind capacity coupled with use of hydrogen as a fuel.[147] In this scenario, hydrogen is produced using electrolysers powered by wind energy. The 750 MW of capacity is enough for the needs of 300,000 fuel cell passenger cars. For wind costs of $0.05 per kWh, hydrogen can be generated at about $25 per gigajoule (GJ).[148] Hydrogen compression, storage, local

[145] DOE 1992, page A-15.
[146] Very small amounts of nitrogen oxides (NOx) may be emitted by catalytic heaters using hydrogen, but the amounts are negligible. Ogden and Nitsch in Johansson et al., eds. 1993, page 926.
[147] Ogden and Nitsch in Johansson, et al. 1993, page 979.
[148] A gigajoule is a unit that measures the quantity of energy, just like a "kilowatt-hour" is a measure of a specific quantity of energy. A gigajoule is equal to 1,000,000,000 joules (one billion joules). A kilowatt-hour is equal to 3,600,000 joules (3.6 million joules). Because both gigajoules and kilowatt-hours are both

distribution, and filling station costs add another $8 per GJ, for a total of about $33 per GJ. In order to compare the cost of hydrogen fuel cell cars to gasoline powered internal combustion engine cars, the authors developed lifecycle costs for both types of vehicles.[149] With delivered hydrogen roughly $33 per GJ, the lifecycle costs of a hydrogen fuel cell vehicle is equivalent to a gasoline-powered vehicle at gasoline costs of $1.66 per gallon.[150] While gasoline is cheaper than this in the United States, it is much more expensive in many countries.[151] Use of hydrogen from wind power does not produce local air pollution, global warming, or acid rain, does not rely on a non-renewable resource concentrated in only a few places, and does not produce other negative environmental or social impacts associated with use of oil.

As can be seen above, the cost of hydrogen production is the largest component of the hydrogen system. Since breeder reactor electricity costs will be 2-3 times higher than for offshore wind electricity, the cost of delivered hydrogen from the breeder reactor scenario will clearly be much greater than for the wind scenario. With electricity costs of 11 to 15 cents per kWh for breeder reactors, delivered hydrogen costs would be roughly double those of a wind energy system.

The case could be made that electricity from breeder reactors used in battery-powered electric vehicles could compete with hydrogen from wind energy in the transportation sector. Electricity costs of $0.11 to $0.15 per kWh are equivalent to $31 to $45 per GJ of energy. The optimistic $0.11 per kWh for breeder reactors is roughly equivalent to the $33 per GJ for delivered hydrogen from offshore wind electricity at $0.05 per kWh. However, this comparison fails to account for battery costs and potential inefficiencies from frequent charging and discharging of batteries.

Our evaluation of the long-term issues associated with both wind energy and breeder reactor technology indicates that, even considering additional costs for energy storage to compensate for the intermittent nature of the wind, wind energy is more attractive than breeder reactors.

Conclusions

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measures of energy, we can compare hydrogen costs in "$ per GJ" from electricity costs "cents per kWh" – as we do in the text.

[149] Lifecycle cost accounting is a methodology for estimating the total costs over the life of a vehicle – initial cost, fuel cost, insurance, maintenance, etc. It is important to compare not just the fuel costs (i.e., hydrogen vs. gasoline) but rather the total cost of a vehicle over its lifetime. This is especially important when comparing technologies that may have higher initial capital or fuel costs but which are much more efficient and also likely to last longer (fuel cell vehicles are expected to last longer partly because fuel cells do not have moving parts, unlike internal combustion engines).

[150] Ogden and Nitsch in Johansson et al., eds. 1993, pages 978-979.

[151] The average cost of gasoline in the United States (all grades) was $1.29, including $0.43 in taxes (API 1998). In many European countries, retail costs for premium gasoline were between $3 and $4 in 1998 (EIA 1999). Retail costs for gasoline include taxes, part of which is for environmental damages. Ideally, wind-derived hydrogen should not be taxed as heavily as gasoline, if at all, since it does not have as high deleterious environmental consequences.

This comparison of offshore wind energy costs with those incurred for plutonium fuel demonstrates that, on economic grounds alone, Japan is seriously misallocating its public energy development resources. Japan's MOX fuel program is an intermediate step to an even more costly fast breeder reactor program. In the long-term, a large scale program of offshore wind development is clearly a preferable investment to breeder reactor technology. Thus, the justification for an expensive program to use MOX in light water reactors as an intermediate step must not rest on short- and medium-term economic considerations alone. However, our analysis shows that wind energy is more economical even within these time frames. We estimate that its cumulative costs to the year 2010 would be hundreds of millions or possibly billions of dollars lower than MOX energy costs.

There is only limited experience in offshore wind energy development, however, and it is entirely in Europe. Further work is needed urgently in Japan to identify the most promising sites that do not conflict with other uses. A vigorous offshore wind energy program could result in annual wind energy generation almost equal to the current optimistic MOX fuel use schedule. Although Japan does have considerable experience in major construction projects such as would be required for realization of offshore wind farms, early efforts will likely have to rely on wind energy engineering expertise developed in Europe and the United States. Over time, however, there is no reason why Japan cannot become a world leader in this field.

4. Some policy issues relating to wind power development

Wind power development received a boost, along with other renewable sources of energy after the increases of oil prices during 1973-74 and against during 1979-80. The expenditures on research and development were justified on grounds of energy self-sufficiency, environmental desirability, and an assumption that oil prices would remain high. The approach used to develop the world's first large-scale wind farm in California was to subsidize the capital cost of wind power station installation. We will take a brief look at the case of wind power in California.

Several factors led to the creation of the wind farms specifically in California. Resource assessments began in the 1970s and identified key wind resource areas in the state.[152] Substantial research and development efforts were also undertaken. The Public Utility Regulatory Policy Act (PURPA), a piece of federal legislation passed in 1978, created a market for independent power producers by requiring electric utilities to purchase electricity at their "avoided cost."[153] Other federal incentives included a 15% tax credit for certain energy sources, including wind.[154]

These policies did not spur much wind power around the U.S., however. The key piece of legislation that led to the wind energy boom in California was an additional investment tax credit of 25%.[155] This additional tax credit created the right conditions to attract significant amounts of capital needed to develop wind turbine technology. In 1980, the California Energy Commission set a goal of 500 MW of wind capacity by 1985; some 1,141 MW of wind capacity were actually installed by 1985.[156] By 1987, wind capacity in California was over 1,400 MW – constituting the vast majority of U.S. wind capacity, and an amount larger than any other country until Germany surpassed it in 1997.

The policies for wind energy development in California had their drawbacks, however. The investment tax credits were important in attracting capital and allowing for investment to develop and improve technology, but they were also subject to abuse. One study remarked that "some manufacturers were more devoted to the sale of tax shelters than the development of a reliable wind turbine" and noted that The study also observed that "most investments failed to live up to their promised levels of availability or

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[152] Interestingly, California was apparently identified as a "wind poor" state in early evaluations by the Department of Energy. Rakow 1993, page 11.

[153] That is, utilities were required to purchase electricity from qualified facilities by offering contracts at a cost equivalent to what it would cost them to generate more electricity. The exact details for calculation of the "avoided cost" are complex – for example, they depend on the time frame under consideration. For a discussion, see Berger 1997, page 362 note 10. (Berger also cites Hamrin and Rader, *Investing in the Future: A Regulator's Guide to Renewables*, National Association of Regulatory Utility Commissioners, Washington, D.C., 1994.)

[154] The investment tax credit was contained in The Energy Tax Act of 1978 (Public Law 95-618). It expired on December 31, 1985. Cox, Blumenstein, and Gilbert 1989, pages 9-10.

[155] The California 25% investment tax credit for renewable energy sources was in effect until December 31, 1985, when it was replaced with a 15% investment tax credit until December 31, 1986, when the program ended. Cox, Blumenstein, and Gilbert 1989, page 10.

[156] Cox, Blumenstein, and Gilbert 1989.

production."[157] The deadlines established for some of the tax incentives also resulted in a rush to install turbines. This resulted in installation of turbines of poor quality and insufficient attention to siting issues such as turbine wake effects and environmental impacts. Finally, when the tax breaks disappeared – and oil prices fell – wind power development tapered off.

The California experience calls into question the wisdom of basing incentives on turbine capital cost rather than performance. Although it had the distinction of having the most concentrated wind power capacity for many years after the investment tax program ended, development slowed after they were repealed in the mid-1980s and in fact California wind power capacity has been declining since 1991.[158] The policy experience in the United States, and also in some other countries, has created cycles of "boom and bust" rather than encouraging stable markets for introducing new energy technologies and systematically reducing their costs over time. In the United States, the most recent "boom" cycle began in 1998 (an estimated 235 MW were installed in the United States, mostly in Minnesota, Wyoming, and Oregon[159]) is only expected to continue until mid-1999, the deadline for projects to be eligible for another incentive, the Production Tax Credit.[160] When the Production Tax Credit expires in June 1999, wind energy development in the United States may again experience a slowdown.

Denmark and Germany have used policies in the form of guarantees for the purchase of power to become the largest actors in wind energy development at the turn of the century – Germany has the highest installed capacity of any country and Danish manufacturers account for 60% of the $1.5 billion global wind industry market.[161] Denmark originally provided small investment tax credits, but this policy quickly gave way to one of guaranteed purchase of power. The U.S. Office of Technology Assessment (OTA) noted that "the Danish government has opted to pursue direct market stimulation in the form of subsidies rather than implement an extensive R&D program," noting that Danish government R&D expenditures in the 1980's was limited to only about $95 million.[162]

Guaranteed purchase of power, also known as Renewable Energy Feed-in Tariffs (REFITS), is evidently superior as a method of encouraging development of a technology to subsidies on capital cost because it requires performance over a period of time for investors to actually recover their investment. However, this manner of subsidy does not necessarily encourage a systematic reduction in cost.

For technologies that are close to commercialization and are desirable on environmental or security grounds, public monies should be invested in a manner that encourages both

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[157] Cox, Blumenstein, and Gilbert 1989, page 4.
[158] Older turbines in California have been replaced with newer ones as part of "repowering" projects, but the overall decline between 1991 and 1997 was 11%. Gipe 1998.
[159] Worldwatch Institute, 1999.
[160] The Production Tax Credit is part of the Energy Policy Act of 1992, codified in Section 45 of the Internal Revenue Service Code. The tax credit is 1.5 cents per kilowatt-hour for electricity generated from qualified sources. AWEA 1994.
[161] Greenpeace 1998.
[162] OTA 1995, pages 243-245.

performance and investment of private funds in research and development to lower costs. The installation of substantial amounts of wind power in the short-and medium-term as a way to reduce greenhouse gas emissions and achieve other environmental and on-proliferation goals is highly desirable. The question is how taxpayer and ratepayer resources should be invested so that the cost of achieving these desirable objectives is minimized.

A review of the past record of government policies to encourage wind power indicates that purchase each year by public authorities and/or utilities of pre-specified amounts of capacity by open bid would achieve the desired goals of stimulating a transition to an energy future that is environmentally sound and does not pose proliferation risks. The government would specify the areas, including offshore regions, in advance and private parties would bid to supply electricity over a 15 to 20 year period at prices specified in advance. This would encourage private research and development and performance-based competitive bidding that would efficiently use public resources and systematically lower costs.

For the United States, we propose the government purchase 1,000 megawatts a year of wind capacity at least until the year 2010 at which point a major evaluation should be completed. Sites could be selected based on a number of criteria such as nature of the wind resource, regional energy needs, sites with minimal land impacts, and ecosystem impacts. The bids should require guaranteed performance over a specified period of time, on, in return for long-term contracts. Projects would have a period of a few years (enough to ensure all permits can be obtained and projects are properly planned out) to be implemented.

This would be somewhat analogous to the way in which leases for petroleum exploration are put up for bid in the United States, with the difference that in the case of wind the approximate size of the resource is already known. Hence contracts would be for actual delivery of wind-generated electricity (rather than exploration, which is the objective in petroleum leases).

A similar program is the "Non Fossil Fuel Obligation" program (NFFO), which began in England and Wales in 1989.[163] The original goal of 1,200 MW of "Declared Net Capacity" by the year 2000 was increased to 1,500 MW in 1995. Contracts were awarded for different renewable energy technologies. The difference between renewable and conventional sources is paid out of a tax levied on users of fossil fuel electricity. Every few years, a new round of contracts were let. The first two rounds, in 1990 and 1991, paid a premium price for electricity generated before 1998. As it turned out, a major weakness of this program was the short-term contracts. The result was high costs, since high capital cost investments had to be recovered in the space of only a few years. In addition, planning delays shortened the already short deadline for the program. Consequently, the program was revised for the third round, providing 15-year contracts and up to a five year period for the project to begin. Lindley (1996) observes, "as a result prices bid…fell substantially and went a long way to dispel the image that electricity

[163] Details of the NFFO program taken from Lindley 1996 and Alder 1998.

from renewables was expensive." Indeed, costs for wind projects in round 3 were less than half of those in rounds 1 and 2, and the costs in round 4 were even lower. Another significant factor for lower costs was improvement in technology.

Our proposal should be one part of a comprehensive strategy to transition to renewable resources and reduction of greenhouse gas emissions. Specifically, our proposal for 1,000 megawatts per year is a program in the federal government. Investments by private utilities, independent power producers, state and local governments, and municipal and cooperative utilities would be in addition to that program.

References

Albright, Berkhout, and Walker 1997	Albright, D., F. Berkhout, and W. Walker, Plutonium and Highly Enriched Uranium 1996, Oxford University Press.
Alder 1998	Alder, M., "Renewable Energy Trading Experience," *Proceedings, World Renewable Energy Congress V: Renewable Energy: Energy Efficiency, Policy, and the Environment*, edited by A.A.M. Sayigh, 20-25 September, Florence, Italy.
Asmus 1997	Asmus, P., "Demand for hold on wind funding," *Wind Power Monthly*, January.
API 1998	American Petroleum Institute, *How Much We Pay for Gasoline: 1997 Annual Review*, API Policy Analysis and Strategic Planning Department, April.
AWEA 1998a	American Wind Energy Association, *International Wind Energy Capacity Projections*, Washington, D.C., April.
AWEA 1998b	American Wind Energy Association, *Wind Energy and Climate Change*, Washington, D.C.
AWEA 1998c	American Wind Energy Association, "Altamont Repower Project Could Reduce Bird Collisions," *Windletter*, Vol. 25, No. 11, November.
AWEA 1997	American Wind Energy Association, *A Status Report on International Utility-Scale Wind Energy Markets*, Washington, D.C., April 28.
AWEA 1994	American Wind Energy Association, *The Wind Energy Production Tax Credit: A User's Guide*, Washington, D.C.
Barthelmie et al. 1996	Barthelmie, R.J., M.S. Courtney, J. Højstrup, and S.E. Larsen, "Meteorological aspects of offshore wind energy: Observations from the Vindeby wind Farm," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 62, pages 191-211.
Berger 1997	Berger, J.J., *Charging Ahead: The Business of Renewable Energy and What It Means for America*, New York: Henry Holt.
Border 1998	Border Wind Limited, Northumberland U.K., "Offshore Wind Energy: Building a New Industry for Britain," prepared for Greenpeace, June.
BTM 1998	BTM Consult ApS, *International Wind Energy Development: World Market Update 1997: Forecast 1998-2002*, Ringkobing, Denmark, March.
CNIC 1998	Citizens' Nuclear Information Center, *Nuke Info Tokyo*, Tokyo, July/August.
CNIC 1997	Citizens' Nuclear Information Center, *Comprehensive Social Impact Assessment of MOX Use in Light Water Reactors, Final Report of the International MOX Assessment*, by J. Takagi, M. Schneider, F. Barnaby, I Hokimoto, K. Hosokawa, C. Kamisawa, B. Nishio, A. Rossnagel, M. Sailer, Tokyo: IMA Project, CNIC, November.
CNIC 1996	Citizens' Nuclear Information Center, *Nuke Info Tokyo*, Tokyo, January/February.
Cohn 1997	Cohn, S.M., *Too Cheap to Meter: an Economic and Philosophical*

	Analysis of the Nuclear Dream, Albany: State University of New York.
Cox et al. 1989	Cox, A., C. Blumstein, and R. Gilbert, *Wind Power in California: A Case of Targeted Subsidies*, Universitywide Energy Research Group, University of California, UER-191, April.
Dahl 1997a	Dahl, K., "Heavyweights back development plans," *Windpower Monthly*, Vol. 13 (10), October, page 20.
Dahl 1997b	Dahl, K., "Japanese firm makes solid commitment: Massive investment by Tomen in series of European wind farms," *Windpower Monthly*, Vol. 13(6), June, page 18.
Dahl 1997c	Dahl, K., "Government Subsidy Programme for Wind," *Windpower Monthly*, Vol. 13(6), June, page 8.
Danish Energy Agency 1997	Danish Energy Agency, *Offshore Wind Turbines, Press Release*, October 3.
Danish Energy Agency 1996	Danish Energy Agency, *Energy 21: The Danish Government's Action Plan for Energy*, Ministry of Environment and Energy, April.
Davidson 1998	Davidson, R., "New Rules for the Altamont Pass," *Windpower Monthly*, July.
DOE 1992	U.S. Department of Energy, *Hydrogen Program Plan, FY 1993 – FY 1997, Office of Conservation and Renewable Energy*, DOE/CH10093-147, DE92010556, Golden, CO: National Renewable Energy Laboratory, June.
DOE 1987	Elliot, D.L., C.G. Holladay, W.R. Barchet, H.P. Foote, W.F. Sandusky, *Wind Energy Resource Atlas of the United States*, prepared for the U.S. Department of Energy by Pacific Northwest Laboratory, Richland, WA, March.
Doherty 1995	Doherty, J.P., "U.S. Wind Energy Potential: The Effect of Proximity of Wind Resources to Transmission Lines," *Monthly Energy Review*, U.S. Energy Information Administration, February.
DWTMA 1998	Danish Wind Turbine Manufacturers Association web page, *www . windpower . dk*, March 10.
EdF 1998	Electricité de France, *Press File: Superphénix; Creys-Malville*, February 3.
EIA 1999	Energy Information Administration, *Weekly Retail Premium Gasoline Prices (Including Taxes)*, U.S. Department of Energy, January 11. *www .eia.doe.gov/emeu/international/gas1.html*
EIA 1996	Energy Information Administration, *Annual Energy Outlook 1997: With Projects to 2015*, DOE/EIA-0383(97), U.S. Department of Energy, December.
ELKRAFT 1997	Offshore Wind-Farm Working Group of the Electricity Companies and the Danish Energy Agency, *Action Plan for Offshore Wind Farms in Danish Waters*, edited by ELKRAFT v/SEAS Wind Power Department, Haslev, Denmark, September.
EWEA 1998	European Wind Energy Association, "Wind Energy to Provide 10% of European Electricity Needs," *Press Release*, Aarhus, Denmark: June

	22.
FEPC 1998	Federation of Electric Power Companies/Japan, *Japan's MOX Program*," Press Release, Washington, D.C., August.
FEPC 1997a	Federation of Electric Power Companies/Japan, *Electricity Review Japan – 1997*, Tokyo.
FEPC 1997b	Federation of Electric Power Companies/Japan, *Fact Sheet on Japan's MOX Program*, Washington, D.C., February.
Ferguson 1997	Ferguson, M. "Structural and Economic Optimisation of OWEC Support Structure: Contribution to the Joule III Project Opti-OWECS," *Wind Engineering*, Vol. 21, No. 5, pages 339-350.
Flavin 1996	Flavin, C., "Vital Sign" Windpower: Small, But Growing Fast," *World Watch*, Worldwatch Institute, September/October.
French Accounting Office 1996	French Accounting Office, *Rapport particulier sur les comptes et la gestion de la NERSA (Centrale nucléaire européenne à neutrons rapides), 1990-1994*, December 16.
Fuglsang and Thomsen 1998	Fuglsang, P., and K. Thomsen, *Cost Optimization of Wind Turbines for Large-Scale Offshore Wind Farms*, Risø-R-1000(EN), Risø National Laboratory, Roskilde, Denmark, February.
Gaudiosi 1996	Gaudiosi, G., "Offshore Wind Energy in the World Context," *Renewable Energy*, vol.9, no. 1-4, Sept.-Dec. 1996, pages 899-904.
Gipe 1998	Gipe, P., "Overview of Worldwide Wind Generation," *Proceedings, World Renewable Energy Congress V: Renewable Energy: Energy Efficiency, Policy, and the Environment*, edited by A.A.M. Sayigh, 20-25 September, Florence, Italy.
Greenpeace 1998	Greenpeace International (Amsterdam), *Danish Wind Energy: An Industrial Success Story*, Briefing Materials.
Halfpenny et al. 1995	Halfpenny, A., S. Kerr, M. Quinlan, and N.W. Bishop, "A technical feasibility study and economic assessment of an offshore floating wind farm," in *Wind Energy Conversion 1995*, ed. by J.A. Halliday, 17th British Wind Energy Association Conference on Wind Energy Conversion, pages 191-197.
Harrison, Knight, and Moller, 1998	Harrison, L., S. Knight, and T. Moller, "Cyclone winds exceeded survival margins," *Windpower Monthly*, Vol. 14(9):20-21.
Harrison 1996	Harrison, L., "Low flying ducks might be at risk," *Windpower Monthly*, Vol. 12(10):26.
Heronemus 1973a	Heronemus, W.E., "Wind Power: A Near-Term Partial Solution to the Energy Crisis," in *Perspectives on Energy: Issues, Ideas, and Environmental Dilemmas*, ed. by L.C. Ruedisili and M.W. Firebaugh, New York: Oxford University Press, 1975, pages 364-376.
Heronemus 1973b	Heronemus, W., "A Proposed National Wind Power R&D Program," in *Wind Energy Conversion Systems, Workshop Proceedings*, Washington, D.C., June 11-13, 1973, National Aeronautics and Space Administration, PB-231 341, prepared for National Science Foundation, December, pages 197-203.
Heronemus	Heronemus, W.E., "Power from the Offshore Winds," in *Applications of*

1972	*Marine Technology to Human Needs, Preprints*, 8th Annual Conference and Exhibition, Marine Technology Society, Washington, D.C., September 11-13, pages 435-466.
IEA 1998	International Energy Agency, *IEA Wind Newsletter*, Issue No. 12, January.
IEA 1997	International Energy Agency, *IEA R&D Wind Annual Report 1996*, Chapter on Japan. [This chapter taken from the 1996 annual report, presumably published in 1997. See IEA 1996 below for details.]
IEA 1996	International Energy Agency, *IEA R&D Wind Annual Report 1995*, Executive Committee for the Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems, U.S. National Renewable Energy Laboratory; Golden, CO: March.
Iida 1999	Iida, T., Senior Researcher, Dept. of Environmental & Social Policy Studies, Japan Research Institute, Tokyo, personal communication, January 5, 6, and 8.
Iida 1998	Iida, T., “Greening of Electricity – A Japan Case,” Presentation at The Workshop on Sustainable and Peaceful Energy Future in Asia ’98, organized by Citizen’s Nuclear Information Center (Tokyo) and Joint Institute for a Sustainable Energy and Environmental Future (Seoul), September 28-30, Hoam Guest House, Seoul, South Korea.
Japan Electric Power Survey Committee 1998	Japan Electric Power Survey Committee, *1998 Electric Power Survey – 92nd Semi-Annual Report, April 1, 1998*, June.
JEPIC 1997a	Japan Electric Power Information Center, *Electric Power Industry in Japan 1997/98*, Tokyo, Japan.
JEPIC 1997b	Japan Electric Power Information Center, *Statistical Handbook 1997-98 – Electric Utility Industry in Japan*, Tokyo, Japan.
Johansson et al., eds. 1993	Johansson, Thomas B., Henry Kelly, Amulya K. N. Reddy, Robert H. Williams, *Renewable Energy: Sources for Fuels and Electricity*, Washington, D.C. : Island Press.
Kajita 1999	Kajita, Director of New Energy and Industrial Technology Development Organization (NEDO) Washington, D.C. Office, personal communication, January 8.
Krohn 1998	Krohn, S., *Offshore Wind Energy: Full Speed Ahead*, Danish Wind Turbine Manufacturers Association web page.
Krohn 1997	Krohn, S., “The Energy Balance of Modern Wind Turbines,” Danish Wind Turbine Manufacturers Association, *Wind Power Note*, No. 10, December.
Kühn and Bierbooms 1996	Kühn, M., and W.A.A.M Bierbooms, “Structural and Economic Optimization of Bottom-Mounted Offshore Wind Energy Converters (Opti-OWECS): Overview and Results of the First Phase,” *Proceedings of the European Wind Energy Conference 1996*, Göteborg, Sweden, 20-24 May.
Kühn et al. 1998	Kühn, M., W.A.A.M. Bierbooms, G.J.W. van Bussel, M.C. Ferguson, B. Göransson, T.T. Cockerill, R. Harrison, L.A. Harland, J.H. Vugts, R.

	Wiecherink, *Structural and Economic Optimisaton of Bottom-Mounted Offshore Wind Energy Converters: Executive Summary, Opti-OWECS Final Report, Volume 0*, EU Joule II Project JOR3-CT95-0087. Delft, The Netherlands: Institute for Wind Energy, Delft University of Technology, (IW-98139R), August.
Kühn et al. 1997	Kuhn, M., W.A.A.M. Bierbooms, T.T. Cockerill, M. Ferguson, B. Göransson, J.H. Vugts, *Structural and Economic Optimization of Offshore Wind Energy Converters: Overview of Second Phase of the Joule III Project Opti-OWECS*.
Kühn et al. 1996	Kühn, M., T. Pauling, and S. Köhler, "Cost analysis and optimization of offshore wind farms," *Proc.: European Union Wind Energy Conference 96*, Göteburg, Sweden, 20-24 May.
Leventhal and Dolley 1994	Leventhal, P. and S. Dolley, "A Japanese Strategic Uranium Reserve: A Safe and Economic Alternative to Plutonium," *Science and Global Security*, Vol. 5, No. 1, pages 1-31.
Leventhal 1992	Leventhal, P., Testimony, Hearing on the Threat of North Korean Proliferation Subcommittee on East Asian and Pacific Affairs, U.S. Senate Committee on Foreign Relations, January 14.
Lindley 1996	Lindley, D., "The Wind Energy Market in the U.K. and Ireland," *Proceedings, American Wind Energy Association Windpower '96*, June 23-27, pages 67-76.
MAFF 1998	Ministry of Agriculture, Fisheries and Food, "Radioactive Contaminated Pigeons in Seascale village," *Incidence surveillance report*, 13 March. (www. maff.gov.uk/food/incid_1/bnfp23.htm)
Makhijani 1997	Makhijani, A., "Technical Aspects of the Use of Weapons Plutonium as Reactor Fuel," *Science for Democratic Action,* Vol. 5, No. 4, Takoma Park, MD : IEER Press, February.
Makhijani 1996	Makhijani, A., "Plutonium as an Energy Source," *Energy and Security*, No. 1, Takoma Park, MD : IEER Press.
Makhijani and Saleska 1996	Makhijani, A., and S. Saleska, *The Nuclear Power Deception: U.S. Nuclear Mythology from Electricity 'Too Cheap to Meter' to 'Inherently Safe' Reactors*, Takoma Park, MD : Institute for Energy and Environmental Research, April.
Mastuyama 1999	Matsuyama, K., New Energy and Industrial Technology Development Organization (NEDO) Washington, D.C. Office, personal communication, January 6.
MITI/ANRE 1998	Ministry of International Trade and Industry, Agency of Natural Resources and Energy, *Long-term Outlook of Japanese Energy Supply and Demand*, Energy Policy Planning Division, June.
MITI/ANRE 1997	Ministry of International Trade and Industry, Agency of Natural Resources and Energy, *Energy in Japan: Facts and Figures*, August.
Nagai, Ushiyama, and Ueno 1997	Nagai, H., I. Ushiyama, and Y. Ueno, "Feasibility Study of Offshore Wind Power Generation in Japan," *Proceedings of the 19th Wind Energy Symposium of the Japan Wind Energy Association*, Tokyo, November 20-21, pages 128-131. [Citation in Japanese.]
Nakada 1995	Nakada, K., "Wind Energy Generation: Industry Sector Analysis," US

	& Foreign Commercial Service," July. [check www.gwjapan.com]
NAS-NRC 1996	National Research Council of the National Academy of Sciences, *Nuclear Wastes: Technologies for Separations and Transmutations*, Committee on Separations Technology and Transmutation Systems, Board on Radioactive Waste Management, Commission on Geosciences, Environment, and Resources, National Research Council, Washington, D.C.: National Academy Press.
NAS 1995	National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options*, Panel on Reactor-Related Options for the Disposition of Excess Weapons Plutonium, Committee on International Security and Arms Control, National Academy of Sciences, Washington, D.C.: National Academy Press.
NEDO 1997	New Energy and Industrial Technology Development Organization, "*Development of Large-scale Wind Power Generation Systems*, Solar Energy Department, November.
Northern States Power 1995	Northern States Power Company, "NSP Names Zond as Wind Energy Supplier," *Press Release*, Minneapolis, MN: June 21.
NREL 1996	National Renewable Energy Laboratory, *Wind Energy Information Guide*, produced for the U.S. Department of Energy, DOE/GO-10095-238 / DE96000474, Washington, D.C. April.
NWCC 1997	National Wind Coordinating Committee, "Wind Energy Environmental Issues," *Wind Energy Series*, No. 2, January.
OECD 1998	Organization for Economic Cooperation and Development, "Main Economic Indicators – Purchasing Power Parities," *www . oecd . org* April.
OTA 1995	U.S Congress, Office of Technology Assessment, *Renewing Our Energy Future*, OTA-ETI-614, Washington, D.C.: U.S. Government Printing Office, September.
PNL 1991	Elliot, D.L., Windell, L.L., and Gower, G.L., *An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States*, Pacific Northwest Laboratory, PNL-7789 / UC-261 / DE91-018887, Richland, WA, August.
PNL 1987	Pacific Northwest Laboratory, *Wind Energy Resource Atlas of the United States*, report prepared for the U.S. Department of Energy, DOE/CH10094-4; DE86004442; UC Category:60; Golden, CO: March.
Rakow 1993	Rakow, S., "Wind Energy in California: A Decade of Progress," in *Windpower '93 Proceedings*, San Francisco, CA, July 12-16, Washington, D.C. : American Wind Energy Association
Rambøll 1997	Birck, C., C. Gormsen, S. Lyngesen, J.L. Rasmussen, and H. Juhl, "Cost-Efficient Foundation Structures for Large Offshore Wind Farms," paper presented at Offshore Wind Energy in Mediterranean and Other European Seas Conference, La Maddealena (Sardinia), Italy, 10-11 April 1997, Virum Denmark : Rambøll, Hannemann or Højlund A/S.
REUTERS 1998	Schmelz, A., "Norway Blames Britain for radiation in lobsters," REUTERS, Oslo: February 25.

Sachs 1996	Sachs, N., *Risky Relapse into Reprocessing : Environmental and Non-Proliferation Consequences of the Department of Energy's Spent Fuel Management Program.*, Takoma Park, MD : Institute for Energy and Environmental Research, January.
Takagi 1997	Takagi, J., "International Reprocessing Report: Japan," *Energy and Security*, No. 2, Takoma Park MD : IEER Press, page 5.
Ushiyama 1998a	Ushiyama, I., Ashikaga Institute of Technology, personal communication, November 16.
Ushiyama 1998b	Ushiyama, I., "Wind Energy Activities in Japan," *Proceedings, World Renewable Energy Congress V: Renewable Energy: Energy Efficiency, Policy, and the Environment*, edited by A.A.M. Sayigh, 20-25 September, Florence, Italy.
Van Bussel and Schöntag 1997	Van Bussel, G.J.W., and Chr. Schöntag, "Operation and Maintenance Aspects of Large Offshore Windfarms," *European Wind Energy Conference*, Dublin, Ireland, 10 – 18 October.
Van Hulle and Rajsekhar 1998	Van Hulle, F., and B. Rajsekhar, "Economic Losses of Wind Farms in India: Effect of Grid Abnormalities," *Proceedings, World Renewable Energy Congress V: Renewable Energy: Energy Efficiency, Policy, and the Environment*, edited by A.A.M. Sayigh, 20-25 September, Florence, Italy.
WindStats 1998	*WindStats Newsletter*, Vol. 11, No. 2, Knebel, Denmark, Spring.
WISE 1997	World Information Service on Energy, "Superphénix Definitely Dead: A Post-Mortem," *Bulletin* #475, July 4.
WISE 1994	Küppers, C., and M. Sailer, *The MOX Industry or The Civilian Use of Plutonium: Risks and Health Effects Associated with the Production and Use of MOX*, World Information Service on Energy, A report from the German and Belgian Sections of the International Physicians for the Prevention of Nuclear War, Antwerp, Belgium: September.
World Bank 1998	The World Bank, *World Development Indicators*, Washington, D.C., March.
Worldwatch Institute 1999	Worldwatch Institute, *Wind power capacity grew rapidly in 1998*, Press release, Washington, D.C., January 4.