The Oil Drum: Net Energy

Discussions about Energy and Our Future

Energy from Wind: A Discussion of the EROI Research

Posted by Nate Hagens on October 19, 2006 - 1:55pm in The Oil Drum: Net Energy
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This is a guest post by Cutler Cleveland. Dr. Cleveland is a Professor at Boston University and has been researching and writing on energy issues for over 20 years. He is Editor-in-Chief of the Encyclopedia of Earth, Editor-in-Chief of the Encyclopedia of Energy, the Dictionary of Energy and the Journal of Ecological Economics. He has particular interest and expertise in the field of net energy analysis.

As the world transitions from fossil based energy systems to a larger portfolio of renewables, the tradeoffs between energy quantity, energy quality and environmental impacts will increasingly need to be compared using meaningful metrics. Wind energy seemingly provides high returns, high quality energy (electricity) with minimal large scale environmental impacts.

The post below the fold is Dr. Cleveland's and Ida Kubiszewski's 2006 meta-analysis on wind, "Energy Return on Investment (EROI) for Wind Energy".**

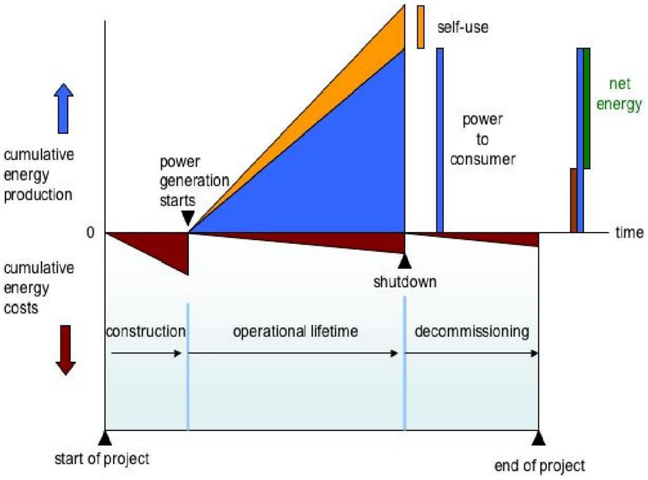
ENERGY RETURN ON INVESTMENT (EROI) FOR WIND ENERGY

Wind energy is one of the fastest growing energy systems in the world. In Europe and the United States, wind-powered generating capacity increased by 18 percent and 27 percent, respectively, in 2005 alone. While the rate of increase is impressive, wind still accounts for less than one percent of the world's electricity generation.

The surge in wind energy is due to a combination of factors, including reduction in the cost of wind turbines, volatile prices for conventional forms of energy, the demand for non-carbon forms of energy to mitigate the effects of climate change, and generous government subsidies such as feed-in tariffs in Europe and the production tax credit in the United States.

One technique for evaluating energy systems is net energy analysis, which seeks to compare the amount of energy delivered to society by a technology to the total energy required to find, extract, process, deliver, and otherwise upgrade that energy to a socially useful form. Energy return on investment (EROI) is the ratio of energy delivered to energy costs. In the case of electricity generation, the EROI entails the comparison of the electricity generated to the amount of primary energy used in the manufacture, transport, construction, operation, decommissioning, and other stages of the facility's life cycle (Figure 1).

Figure 1



Comparing cumulative energy requirements with the amount of electricity the technology produces over its lifetime yields a simple ratio for energy return on investment (EROI):

EROI = (cumulative electricity generated) / (cumulative primary energy required)

This article reviews 112 wind turbines from 41 different analyses, ranging in publication date from 1977 to 2006. This survey shows average EROI for all studies (operational and conceptual) of 24.6 (n=109; std. dev=22.3). The average EROI for just the operational studies is 18.1 (n=158; std. dev=13.7). This places wind energy in a favorable position relative to conventional power generation technologies in terms of EROI.

Methodological Issues

System Boundary

The choice about system boundaries is perhaps the most important decision made in most net energy analyses. One of the most critical differences among the diverse studies is the number of stages in the life cycle of an energy system that are assessed and compared against the cumulative lifetime energy output of the system. These stages include the manufacture of components, transportation of components to the construction site, the construction of the facility itself, operation and maintenance over the lifetime of the facility, overhead, possible grid connection costs, and decommissioning. Energy systems have external costs as well, most notably environmental and human health costs, although these are difficult to assess in monetary and energy terms. No study as yet attempted to assess the environmental costs of wind energy in energy terms.

Methodology

Three types of net energy analysis techniques are used to calculate the net energy derived from wind power: process analysis, input-output analysis, and a hybrid analysis. The assumptions, strengths, and weaknesses of these approaches are discussed here.

Operating Characteristics

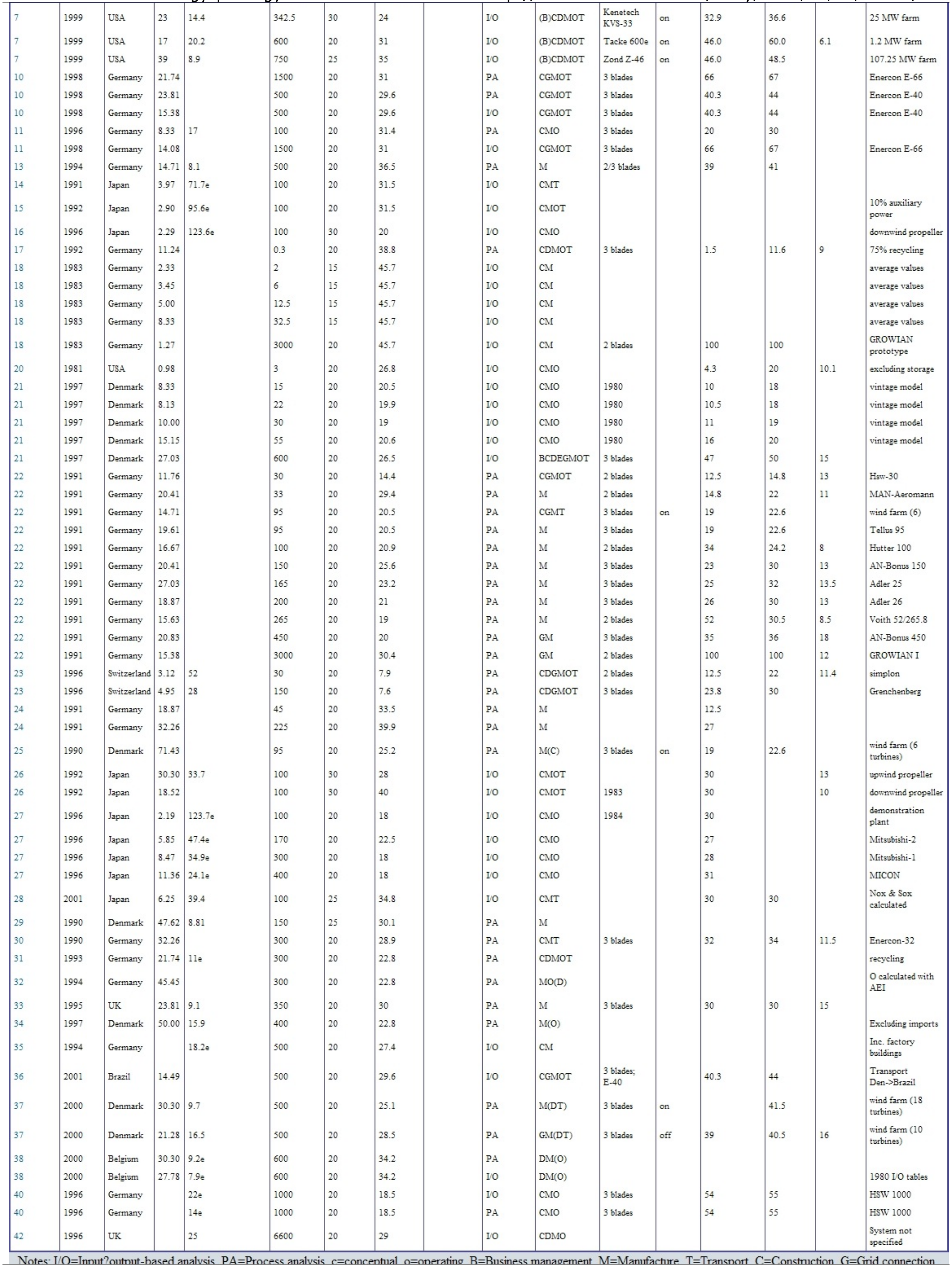
Many analyses must make important assumptions regarding the operating characteristics of wind turbines. These include power rating, assumed lifetime, and capacity factors. Changes in the assumptions made about these factors, or deviations in actual operating conditions from assumed conditions can have a significant impact on results.

Conceptual versus Empirical Studies

Some studies use the theoretical or ideal operating characteristics of a wind turbine that are derived from simulated or assumed costs and operating conditions, e.g., a wind turbine of a given power rating, costing a certain dollar amount, in a location with an assumed wind power density, with an assumed capacity factor, and so on. Of course, actual operating conditions always deviate from assumed conditions. Empirical analyses rely on actual costs, operating conditions, and energy outputs, and thus provide a better metric of an energy system's contribution to a nation's energy supply. This article focuses primarily on empirical studies based on actual operational data.

Results

Reference	Year of Study	Location	EROI	CO2 Intensity (gCO2/kWh)	Power Rating (kW)	Lifetime (yr)	Load Factor (%)	Payback Time (yr)	Analysis Type	Scope as Stated	Turbine Type	On/off shore	Rotor Diameter (m)	Hub Height (m)	Wind Speed (m/s)	Remarks



7	1999	USA	23	14.4	342.5	30	24		I/O	(B)CDMOT	Kenetech KVS-33	on	32.9	36.6		25 MW farm
7	1999	USA	17	20.2	600	20	31		I/O	(B)CDMOT	Tacke 600e	on	46.0	60.0	6.1	1.2 MW farm
7	1999	USA	39	8.9	750	25	35		I/O	(B)CDMOT	Zond Z-46	on	46.0	48.5		107.25 MW farm
10	1998	Germany	21.74		1500	20	31		PA	CGMOT	3 blades		66	67		Enercon E-66
10	1998	Germany	23.81		500	20	29.6		PA	CGMOT	3 blades		40.3	44		Enercon E-40
10	1998	Germany	15.38		500	20	29.6		I/O	CGMOT	3 blades		40.3	44		Enercon E-40
11	1996	Germany	8.33	17	100	20	31.4		PA	CMO	3 blades		20	30		
11	1998	Germany	14.08		1500	20	31		I/O	CGMOT	3 blades		66	67		Enercon E-66
13	1994	Germany	14.71	8.1	500	20	36.5		PA	M	2/3 blades		39	41		
14	1991	Japan	3.97	71.7e	100	20	31.5		I/O	CMT						
15	1992	Japan	2.90	95.6e	100	20	31.5		I/O	CMOT						10% auxiliary power
16	1996	Japan	2.29	123.6e	100	30	20		I/O	CMO						downwind propeller
17	1992	Germany	11.24		0.3	20	38.8		PA	CDMOT	3 blades		1.5	11.6	9	75% recycling
18	1983	Germany	2.33		2	15	45.7		I/O	CM						average values
18	1983	Germany	3.45		6	15	45.7		I/O	CM						average values
18	1983	Germany	5.00		12.5	15	45.7		I/O	CM						average values
18	1983	Germany	8.33		32.5	15	45.7		I/O	CM						average values
18	1983	Germany	1.27		3000	20	45.7		I/O	CM	2 blades		100	100		GROWIAN prototype
20	1981	USA	0.98		3	20	26.8		I/O	CMO			4.3	20	10.1	excluding storage
21	1997	Denmark	8.33		15	20	20.5		I/O	CMO	1980		10	18		vintage model
21	1997	Denmark	8.13		22	20	19.9		I/O	CMO	1980		10.5	18		vintage model
21	1997	Denmark	10.00		30	20	19		I/O	CMO	1980		11	19		vintage model
21	1997	Denmark	15.15		55	20	20.6		I/O	CMO	1980		16	20		vintage model
21	1997	Denmark	27.03		600	20	26.5		I/O	BCDEGMOT	3 blades		47	50	15	
22	1991	Germany	11.76		30	20	14.4		PA	CGMOT	2 blades		12.5	14.8	13	Hsw-30
22	1991	Germany	20.41		33	20	29.4		PA	M	2 blades		14.8	22	11	MAN-Aeromann
22	1991	Germany	14.71		95	20	20.5		PA	CGMT	3 blades	on	19	22.6		wind farm (6)
22	1991	Germany	19.61		95	20	20.5		PA	M	3 blades		19	22.6		Tellus 95
22	1991	Germany	16.67		100	20	20.9		PA	M	2 blades		34	24.2	8	Hutter 100
22	1991	Germany	20.41		150	20	25.6		PA	M	3 blades		23	30	13	AN-Bonus 150
22	1991	Germany	27.03		165	20	23.2		PA	M	3 blades		25	32	13.5	Adler 25
22	1991	Germany	18.87		200	20	21		PA	M	3 blades		26	30	13	Adler 26
22	1991	Germany	15.63		265	20	19		PA	M	2 blades		52	30.5	8.5	Voith 52/265.8
22	1991	Germany	20.83		450	20	20		PA	GM	3 blades		35	36	18	AN-Bonus 450
22	1991	Germany	15.38		3000	20	30.4		PA	GM	2 blades		100	100	12	GROWIAN I
23	1996	Switzerland	3.12	52	30	20	7.9		PA	CDGMOT	2 blades		12.5	22	11.4	simplon
23	1996	Switzerland	4.95	28	150	20	7.6		PA	CDGMOT	3 blades		23.8	30		Grenchenberg
24	1991	Germany	18.87		45	20	33.5		PA	M			12.5			
24	1991	Germany	32.26		225	20	39.9		PA	M			27			
25	1990	Denmark	71.43		95	20	25.2		PA	M(C)	3 blades	on	19	22.6		wind farm (6 turbines)
26	1992	Japan	30.30	33.7	100	30	28		I/O	CMOT			30		13	upwind propeller
26	1992	Japan	18.52		100	30	40		I/O	CMOT	1983		30		10	downwind propeller
27	1996	Japan	2.19	123.7e	100	20	18		I/O	CMO	1984		30			demonstration plant
27	1996	Japan	5.85	47.4e	170	20	22.5		I/O	CMO			27			Mitsubishi-2
27	1996	Japan	8.47	34.9e	300	20	18		I/O	CMO			28			Mitsubishi-1
27	1996	Japan	11.36	24.1e	400	20	18		I/O	CMO			31			MICON
28	2001	Japan	6.25	39.4	100	25	34.8		I/O	CMT			30	30		Nox & Sox calculated
29	1990	Denmark	47.62	8.81	150	25	30.1		PA	M						
30	1990	Germany	32.26		300	20	28.9		PA	CMT	3 blades		32	34	11.5	Enercon-32
31	1993	Germany	21.74	11e	300	20	22.8		PA	CDMOT						recycling
32	1994	Germany	45.45		300	20	22.8		PA	MO(D)						O calculated with AEI
33	1995	UK	23.81	9.1	350	20	30		PA	M	3 blades		30	30	15	
34	1997	Denmark	50.00	15.9	400	20	22.8		PA	M(O)						Excluding imports
35	1994	Germany		18.2e	500	20	27.4		I/O	CM						Inc. factory buildings
36	2001	Brazil	14.49		500	20	29.6		I/O	CGMOT	3 blades; E-40		40.3	44		Transport Den->Brazil
37	2000	Denmark	30.30	9.7	500	20	25.1		PA	M(DT)	3 blades	on		41.5		wind farm (18 turbines)
37	2000	Denmark	21.28	16.5	500	20	28.5		PA	GM(DT)	3 blades	off	39	40.5	16	wind farm (10 turbines)
38	2000	Belgium	30.30	9.2e	600	20	34.2		PA	DM(O)						
38	2000	Belgium	27.78	7.9e	600	20	34.2		I/O	DM(O)						1980 I/O tables
40	1996	Germany		22e	1000	20	18.5		I/O	CMO	3 blades		54	55		HSW 1000
40	1996	Germany		14e	1000	20	18.5		PA	CMO	3 blades		54	55		HSW 1000
42	1996	UK		25	6600	20	29		I/O	CDMO						System not specified

Notes: I/O=Input?output-based analysis, PA=Process analysis, c=conceptual, o=operating, B=Business management, M=Manufacture, T=Transport, C=Construction, G=Grid connection

O=Operation & Maintence, D=Decommissioning, e=CO_2 equivalents including CH_4 and N_2O, ()=partly covered.

The above table provides the detailed technical results of the wind studies. The data include the year and location of the study, key technical assumptions such as load factor, power rating and lifetime, system boundaries, the type of net energy method used, and the EROI. The table also distinguishes between studies based on actual performance of a wind system and conceptual studies based on theory or simulations.

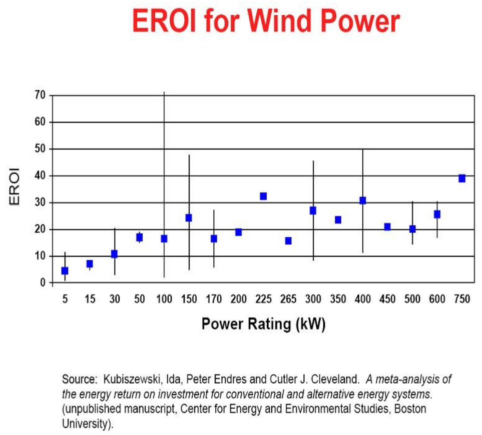
The average EROI for all studies (operational and conceptual) is 24.6 (n=109; std. dev=22.3). The average EROI for just the operational studies is 18.1 (n=158; std. dev=13.7).

Discussion

EROI and Turbine Size

One of the striking features of the studies is that the EROI generally increases with the power rating of the turbine (Figure 2). This is probably due to several reasons: first, smaller wind turbines represent older, less efficient technologies. The new turbines in the megawatt (MW) range embody many important technical advances that improve the overall effectiveness of energy conversion. Although larger turbines require greater initial energy investments in materials, the increase in power output more than compensates for this.

Figure 2: EROI vs. wind turbine power rating.



Source: Kubiszewski, Ida, Peter Endres and Cutler J. Cleveland. *A meta-analysis of the energy return on investment for conventional and alternative energy systems.* (unpublished manuscript, Center for Energy and Environmental Studies, Boston University).

Second, larger turbines have a greater rotor diameter, which determines its swept area, which probably is the single most important determinant of a turbine's potential to generate power. A turbine with respectable power rating but a rotor diameter so small that it can't capture that power until the wind speed reaches very high velocities will not produce a reasonable annual energy output. Again, larger rotors require greater initial energy investments in materials, but the increase in power output more than compensates for this.

These conclusions are consistent with the finding that commercial wind farms have moved towards larger turbines that are less expensive with regard to installation, operation, and maintenance. The greater cost efficiency of larger turbines is largely attributed to economies of scale and learning by doing. Accordingly, under a similar assumption, larger turbines have a greater efficiency in respect to EROI.

Another reason that larger turbines have a larger EROI is the well-known "cube rule" of wind power, i.e., that the power available from the wind varies as the cube of the wind speed. Thus, if the wind speed doubles, the power of the wind increases 8 times. New turbines are taller than earlier technologies, and thus extract energy from the higher winds that exist at greater heights. Surface roughness -- roughness determined mainly by the height and type of vegetation and buildings -- reduces wind velocity near the surface. Over flat, open terrain in particular, the wind speed increases relatively fast with height.

Influence of Production Country

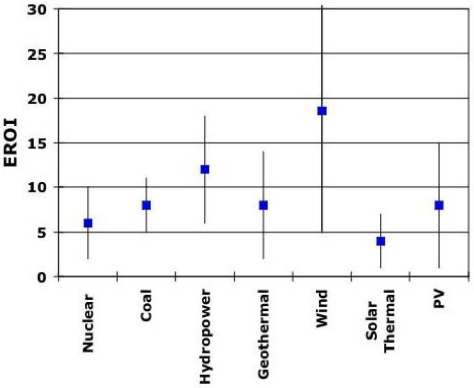
EROI is affected by the location of a turbine's manufacture and installation. An anaysis of the EROI of conceptual wind turbines produced and operated in Germany and Brazil shows a range of 5 to 40:1. Such a large range in wind turbine EROIs is a function of differences in the energy used for transportation of manufactured turbines between countries, the countries' economic and energy structure, and recycling policies.

Production and operation of an E-40 turbine, standing 44 meters high in a coastal region in Germany requires approximately 1.39 times more energy, or 3.9 times more input energy per kWh of output energy, than the production and operation of the same turbine in Brazil. This assumes that Brazil's conversion efficiency in the electricity generation system being above 90% is the main reason for the difference in energy inputs, showing that the production scenario has a greater influence upon the magnitude of input energy than site conditions or transportation.

Comparison with other power systems

The EROI for wind turbines compares favorably with other power generation systems (Figure 3). Baseload coal-fired power generation has an EROI between 5 and 10:1. Nuclear power is probably no greater than 5:1, although there is considerable debate regarding how to calculate its EROI. The EROI for hydropower probably exceed 10, but in most places in the world the most favorable sites have been developed.

Figure 3: EROI of various electric power generators.



Challenges facing wind energy

Does the high EROI for wind power presented here guarantee that wind will assume a major role in the world's power generation system? There are a number of issues surrounding wind energy that require resolution before that happens.

The dramatic cost reductions in the manufacture of new wind turbines that characterized the past two decades may be slowing. Part of the slowing may be due to transient factors such as short-term increases in raw material prices; unfavorable exchange rates; insufficient global and domestic manufacturing capability (exacerbated by short-term uncertainty in government subsidy policies); and exercise of market power by the consolidating manufacturing industry. It also is possible that the industry is experiencing diminishing returns to cost reductions via learning-by-doing.

The uncontrolled, intermittent nature of wind reduces its value relative to operator-controlled resources such as coal, gas, or nuclear generation. Intermittency impacts include the seasonal and diurnal match or mis-match to regional energy demands; the contribution of wind energy to capacity reserves for meeting regional reliability requirements; and the lost value to wind plant owners in surplus generation that occurs when wind power saturates the flexible dispatch portion of grid operations.

Wind energy also affects the overall reliability of the electric power system, which is represented in part by the system reserve margin -- that is, a margin of total installed capacity above projected peak load. The capacity credit of an isolated wind plant is generally equal to its capacity factor during the system's peak load period, which normally is less than an operator-controlled source. As more wind capacity is added to a system within a finite geographic area, it becomes increasingly likely that an "outage" at any given facility will be temporally correlated with an "outage" at a nearby (or even not-so nearby) plant. This tends to reduce the average capacity credit for a wind plant as more such facilities are added in a region.

Much of the wind resource base is located in remote locations, so there are costs of getting the wind from the local point-of-generation to a potentially distant load center. This cost is distinct from the cost of simply interconnecting the site to the nearest transmission line. Even at the relatively low current levels of wind penetration on regional grids, long-distance transmission has already proven to be a significant issue for new wind development in some regions. For example, wind plants in Texas have had to curtail output during hours when regional trunk lines are at physical capacity, and Minnesota and California are currently examining ways to alleviate transmission congestion as more development is proposed in their best wind resource areas. These costs are not reflected in most EROI analyses.

The remoteness of the wind resource base also generates the cost of developing land with difficult terrain or that which is increasingly removed from development infrastructure (such as major roads, rivers, or rails capable of transporting the bulky and heavy construction equipment). To the extent that local roads or bridges cannot accommodate blade shipments in excess of 50 meters (over 160 feet) length or nacelle shipments of 50 tons or more, they must be upgraded, rebuilt, or (retroactively) repaired as a part of the plant development process. Little is known about the extent of these costs.

At about 6 or 7 megawatts per square kilometer of net power potential, wind plants are necessarily spread-out over a significant land area. Thus, wind plants must compete with alternative uses of these land resources. In some cases such as agricultural land, multiple simultaneous use is possible. In other cases the competition is stiff. The value of some lands for other types of development (such as urban or housing development) has limited and will limit wind power location options. This is especially true when the land is a signficant source of aesthetic and/or recreational value.

Another issue confronting wind energy is the uncertainty of future government subsidies. Much of the recent growth on wind energy around the world has been made possible by government subsidies such as the wind energy Production Tax Credit (PTC) in the United States and feed-in tariffs and renewable portfolio standards in Europe. While there is strong support in many nations for such support, shifting political winds can create uncertainty for manufacturers and utilities. For example, the wind PTC in the United States was scheduled to expire on December 31, 2005, but was extended to December 31, 2007 by a federal energy bill. The PTC provides a 1.9 cent-per-kilowatt-hour (kWh) tax credit for electricity generated with wind turbines over the first ten years of a project's operations, and is a critical factor in financing new wind farms. The inconsistent nature of this tax credit has been a significant challenge for the wind industry, creating uncertainty for long-term planning and preventing faster market development.

There is also concern about the impacts of wind energy on birds and bats. Early research on the avian impacts of wind energy at places such as Altamont Pass, California, suggested that the wind turbines killed significant numbers of raptors and other birds. In 2004, a large number of bats were killed by a wind farm in West Virginia. The issues surrounding avian and bat mortality have just begun to be studied, so the full potential risk is largely unknown.

Further Reading

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****Citation**
Cleveland, Cutler and Ida Kubiszewski. 2006. "Energy return on investment (EROI) for wind energy." Encyclopedia of Earth. Eds. Peter Saundry. (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment). [Published October 13, 2006; Retrieved October 14, 2006].