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Meta-analysis of net energy return for wind power systems

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ABSTRACT

This analysis reviews and synthesizes the literature on the net energy return for electric power generation by wind turbines. Energy return on investment (EROI) is the ratio of energy delivered to energy costs. We examine 119 wind turbines from 50 different analyses, ranging in publication date from 1977 to 2007. We extend on previous work by including additional and more recent analyses, distinguishing between important assumptions about system boundaries and methodological approaches, and viewing the EROI as function of power rating. Our survey shows an average EROI for all studies (operational and conceptual) of 25.2 ($n = 114$; std. dev $= 22.3$). The average EROI for just the operational studies is 19.8 ($n = 60$; std. dev $= 13.7$). This places wind in a favorable position relative to fossil fuels, nuclear, and solar power generation technologies in terms of EROI.

1. Introduction

Wind energy is one of the fastest growing energy systems in the world. Global installed annual wind capacity grew by more than 31 percent from 1997 to 2007 as seen in the global annual installed wind power capacity graph created by the Global Wind Energy Council (Fig. 1), and will approach 100,000 MW by the end of 2008 [1]. The surge in wind energy is due to a combination of factors, including reduction in the cost of wind turbines, volatile and high prices for conventional forms of energy, the demand for non-carbon forms of energy to mitigate the effects of climate change, and favorable policies such as feed-in tariffs in Europe and renewable portfolio standards in the United States. Despite the impressive growth, wind energy still accounts for a small fraction of total installed power generation.

Global electricity use is projected to double from 2005 to 2030, with its share of final energy consumption rising from 17 to 22 percent [2]. How will the increase in demand be met, particularly in light to the increasing pressure to reduce carbon emissions? A variety of alternatives are proposed, including wind, biomass, various forms of solar power, nuclear, fossil fuel systems with carbon sequestration, among others. A variety of techniques are available to compare power generation systems, including life cycle analysis (LCA), learning or experience curves, and various forms of economic and financial analysis.

Another 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 [3]. 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 facility's life cycle (Fig. 2). 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):

$$\mathrm{EROI} = (\text{cumulative electricity generated}) / (\text{cumulative primary energy required})$$

This analysis reviews 119 wind turbines from 50 different analyses, ranging in publication date from 1977 to 2007. We extend the work of Lenzen and Munksgaard [4] by including additional and more recent analyses, distinguishing between important assumptions about system boundaries and methodological approaches, and viewing the EROI as function of power rating. Our survey shows average EROI for all studies (operational and conceptual) of 25.2 ($n = 114$; std. dev $= 22.3$). The average EROI for just the operational studies is 19.8 ($n = 60$; std. dev $= 13.7$). This places wind in

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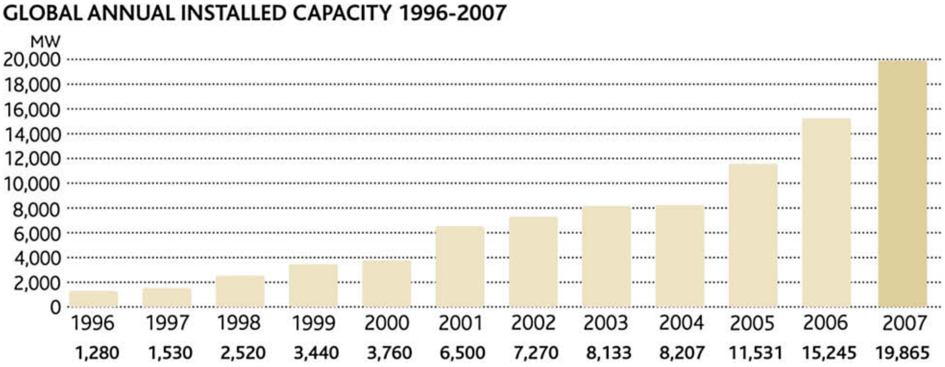

Fig. 1. Global annual installed wind power capacity (Source: Global Wind Energy Council, http://www.gwec.net/, retrieved 9 September 2008.)

a favorable position relative to fossil fuels, nuclear, and solar power generation technologies in terms of EROI.

2. Importance of net energy

Economies with access to energy sources with a large energy surplus have greater potential for economic expansion and/or diversification than those with access to lower quality fuels [5]. The history of the expansion of human civilization and its material standard of living is directly linked to successive access to and development of fuel sources with increasingly greater energy surpluses [6]. The transitions from animate energy sources such as plant, biomass, and draft animals, to wind and water power, to fossil fuels and electricity enabled increases in per capita output due to increases in the quantity of fuel available to produce non-energy goods. The transition to higher surplus fuels also enabled social and economic diversification as decreasing amounts of energy were used in the energy securing process, meaning more fuel was available to support non-extractive activities.

An EROI = 1 is an absolute cutoff point for an energy source, the point at which as much energy is used to deliver a unit of energy as that unit yields. The EROI for crude oil has declined over time, and may continue to do so as the resource base is depleted [7]. Smaller, deeper, and more remote fields require more energy to develop. Alternatives to crude oil such as ethanol from corn and coal liquefaction deliver a lower EROI because a significant amount of energy is needed to process the feedstock itself (corn or coal) [8]. Economic growth and rising standards of living may be more difficult to maintain than they were 50 years ago when wealth was produced by the massive energy surplus associated with the discovery of the Earth's great oil fields in the first half of the twentieth century.

EROI is a tool of net energy analysis, a methodology that 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. Net energy analysis was developed in response to the emergence of energy as an important economic, technological, and geopolitical force following the energy price increases of 1973–74 and 1980–81. Interest in net energy analysis was rekindled in recent years following another round of energy price increases, growing concern about energy's role in climate change, and the debate surrounding the remaining lifetime of conventional fossil fuels, especially crude oil. It typically is assessed along with material flows in life cycle analysis (LCA) of energy systems (e.g., [9]).

3. Methodological issues

3.1. System boundary

The choice about system boundaries is perhaps the most important decision made in net energy analysis, and, for that

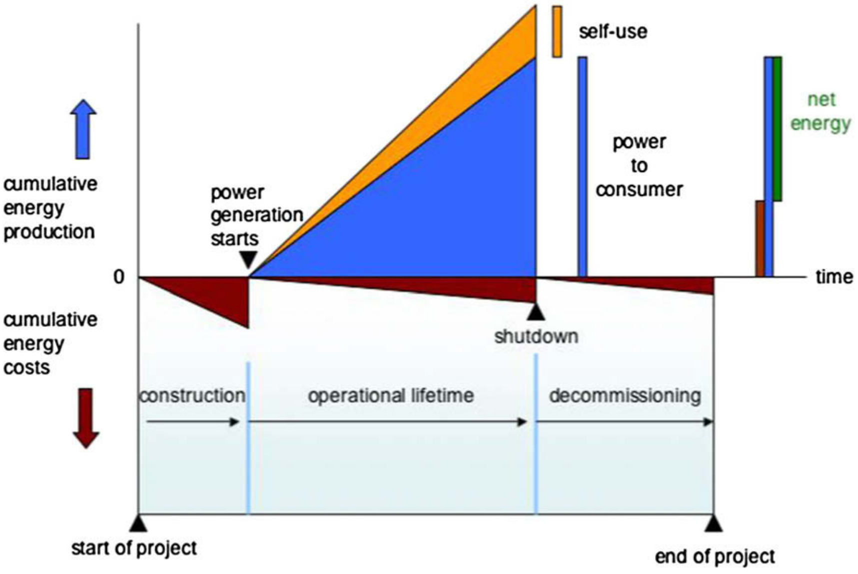

Fig. 2. Energy outputs and energy costs of a power generation facility.

matter, in other analytical approaches a well. 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, decommissioning, and recycling of component materials. 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. External costs are excluded from our analysis.

3.2. Methodology

Two individual types of net energy analysis techniques are used to calculate the net energy derived from wind power: process analysis and input–output analysis. A third type, called hybrid analysis, is a combination of the two. Process analysis assesses the energy used directly in each successive step of the production of a good or service. The energy input–output approach is more comprehensive than process analysis and is analogous to and derived from the input–output matrix used in standard economic analyses. The assumptions, strengths, and weaknesses of the two approaches have been discussed elsewhere in detail (e.g., [10,11]).

3.3. 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.

3.4. 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.

4. Results

Table 1 provides the detailed technical results of the wind studies. The data include 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, certain environmental variables, and 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 25.2 ($n = 114$; std. dev = 22.3). The average EROI for just the operational studies is 19.8 ($n = 60$; std. dev = 13.7).

5. Discussion

5.1. EROI and power rating

One of the striking features of the studies is that the average EROI generally increases with the power rating of the turbine (Fig. 3). Fig. 3 solely looks at operational wind turbines with a power rating below 1 MW. Turbines above 1 MW were not included due to lack of reliable data.

The results found in Fig. 3 may be due to a combination of factors, including larger wind turbines creating economies of scale, more efficient technology, greater rotor diameters increasing the load factor, and higher hub heights providing access to greater wind speeds. These factors are derived from those found to be important in the creation of experience curves which show a decrease of wind turbine price over time [12].

First, smaller wind turbines represent older, less efficient technologies. The new turbines nearing the megawatt (MW) range embody many important technical advances that improve the overall effectiveness of energy conversion. Such developments include improved aerodynamic profiles, increasing the peak efficiency approximately 8% between the early 1980 and early 1990 [13]. Although larger turbines require greater initial energy investments in materials, the increase in power output due to improvements more than compensates for this over the lifetime of the turbine.

Second, larger turbines have a greater rotor diameter, which determines swept area, probably the most important design element that affects generating power potential. High annual energy output will be difficult to obtain if the rotor diameter limits the ability for the turbine to capture the wind power at lower wind speeds, even if turbine power rating is respectable. Again, larger rotors require greater initial energy investments in materials, but the increase in power output more than compensates for this.

Fig. 4 demonstrates how an increase in rotor diameter produces an increase in EROI. These conclusions are consistent with the finding that commercial wind farms have moved towards larger turbines that are less expensive on a levelized basis 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 EROI.

Another reason that larger turbines have a larger EROI is the well known "cube rule" of wind power, i.e., 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 eight times. New turbines are taller than in earlier technologies, and thus extract energy from the higher winds that exist at greater heights. Fig. 5 shows the affect of wind speed on EROI. Surface 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 quickly with height. EROI at location with high wind speeds is also often affected due to limited accessibility to those areas. The installation of wind turbines on mountaintops or far off shore, areas with greatest wind speeds, significantly increases the input energy required in transportation, construction, and connection to the gird.

5.2. Comparison with other power systems

The EROI for wind turbines compares favorably with other power generation systems (Fig. 6). Coal accounts for about 40% of global electricity generation [2] and has an EROI of about 8.0. It is a mature technology where technical improvements are not likely

Table 1
Metadata analysis of wind power systems.

Ref	Year of study	Location	Operational/ conceptual	EROI	CO_2 Intensity (gCO_2/kWh)	Power rating (kW)	Lifetime (yr)	Capacity factor (%)	Energy payback time (yr)	Analysis type	Scope as stated	Turbine information	On/off shore	Rotor diameter (m)	Hub height (m)	Wind speed (m/s)
[4]	1977	USA	c	43.5		1500	30	50.4		I/O	BCEMT	2 blades		60	50	10.5
[4]	1980	UK	c	12.5		1000	25	18.3		I/O	CM		on	46		18.4
[4]	1980	UK	c	6.1		1000	25	18.3		I/O	CM			46		18.4
[4]	1981	USA	o	1.0		3	20	26.8		I/O	CMO			4.3	20	10.1
[4]	1983	Germany	o	2.3		2	15	45.7		I/O	CM					
[4]	1983	Germany	o	3.4		6	15	45.7		I/O	CM					
[4]	1983	Germany	o	5.0		12.5	15	45.7		I/O	CM					
[4]	1983	Germany	o	8.3		32.5	15	45.7		I/O	CM					
[4]	1983	Germany	o	1.3		3000	20	45.7		I/O	CM	2 blades		100	100	
[4]	1990	Denmark	o	71.4		95	20	25.2		PA	M©	3 blades	on	19	22.6	
[4]	1990	Denmark	o	47.6	8.81	150	25	30.1		PA	M					
[4]	1990	Germany	o	32.3		300	20	28.9		PA	CMT	3 blades		32	34	11.5
[4]	1991	Germany	o	18.9		45	20	33.5		PA	M			12.5		
[4]	1991	Germany	o	32.3		225	20	39.9		PA	M			27		
[4]	1991	Germany	c	27.0		300	20	39.9		PA	M			32		
[4]	1991	Germany	c	22.2		3000	20	34.2		PA	M			80		
[4]	1991	Germany	o	11.8		30	20	14.4		PA	CGMOT	2 blades		12.5	14.8	13
[4]	1991	Germany	o	20.4		33	20	29.4		PA	M	2 blades		14.8	22	11
[4]	1991	Germany	o	14.7		95	20	20.5		PA	CGMT	3 blades	on	19	22.6	
[4]	1991	Germany	o	19.6		95	20	20.5		PA	M	3 blades		19	22.6	
[4]	1991	Germany	o	16.7		100	20	20.9		PA	M	2 blades		34	24.2	8
[4]	1991	Germany	o	20.4		150	20	25.6		PA	M	3 blades		23	30	13
[4]	1991	Germany	o	27.0		165	20	23.2		PA	M	3 blades		25	32	13.5
[4]	1991	Germany	o	18.9		200	20	21		PA	M	3 blades		26	30	13
[4]	1991	Germany	o	15.6		265	20	19		PA	M	2 blades		52	30.5	8.5
[4]	1991	Germany	o	20.8		450	20	20		PA	GM	3 blades		35	36	18
[4]	1991	Germany	o	15.4		3000	20	30.4		PA	GM	2 blades		100	100	12
[4]	1991	Japan	o	4.0	71.7e	100	20	31.5		I/O	CMT					
[4]	1992	Germany	o	11.2		0.3	20	38.8		PA	CDMOT	3 blades		1.5	11.6	9
[4]	1992	Germany	c	37.0		300	20	41.9		PA	CDGMOT	3 blades		32	34	
[4]	1992	Japan	o	2.9	95.6e	100	20	31.5		I/O	CMOT					
[4]	1992	Japan	o	30.3	33.7	100	30	28		I/O	CMOT			30		13
[4]	1992	Japan	o	18.5		100	30	40		I/O	CMOT	1983		30		10
[4]	1993	Germany	o	21.7	11e	300	20	22.8		PA	CDMOT					
[4]	1994	Germany	o		18.2e	500	20	27.4		I/O	CM					
[4]	1994	Germany	o	45.5		300	20	22.8		PA	MO(D)					
[4]	1994	Germany	o	14.7	8.1	500	20	36.5		PA	M	2/3 blades		39	41	
[4]	1995	UK	o	23.8	9.1	350	20	30		PA	M	3 blades		30	30	15
[4]	1996	Switzerland	o	3.1	52	30	20	7.9		PA	CDGMOT	2 blades		12.5	22	11.4
[4]	1996	Switzerland	o	5.0	28	150	20	7.6		PA	CDGMOT	3 blades		23.8	30	
[4]	1996	Germany	o		14e	1000	20	18.5		PA	CMO	3 blades		54	55	
[4]	1996	Germany	o		22e	1000	20	18.5		I/O	CMO	3 blades		54	55	
[4]	1996	UK	o		25	6600	20	29		I/O	CDMO					
[4]	1996	Japan	o	2.3	123.6e	100	30	20		I/O	CMO					
[4]	1996	Japan	o	2.2	123.7e	100	20	18		I/O	CMO	1984		30		
[4]	1996	Japan	o	5.8	47.4e	170	20	22.5		I/O	CMO			27		
[4]	1996	Japan	o	8.5	34.9e	300	20	18		I/O	CMO			28		
[4]	1996	Japan	o	11.4	24.1e	400	20	18		I/O	CMO			31		
[4]	1996	Germany	o	8.3	17	100	20	31.4		PA	CMO	3 blades		20	30	
[4]	1996	Germany	c	28.6	10	1000	20	36.2		PA	CMO	3 blades		60	50	
[4]	1997	Denmark	o	8.3		15	20	20.5		I/O	CMO	1980		10	18	
[4]	1997	Denmark	o	8.1		22	20	19.9		I/O	CMO	1980		10.5	18	
[4]	1997	Denmark	o	10.0		30	20	19		I/O	CMO	1980		11	19	
[4]	1997	Denmark	o	15.2		55	20	20.6		I/O	CMO	1980		16	20	
[4]	1997	Denmark	o	27.0		600	20	26.5		I/O	BCDEGMOT	3 blades		47	50	15

(*continued on next page*)

Table 1 (*continued*)

Ref	Year of study	Location	Operational/ conceptual	EROI	CO$_2$ Intensity (gCO$_2$/kWh)	Power rating (kW)	Lifetime (yr)	Capacity factor (%)	Energy payback time (yr)	Analysis type	Scope as stated	Turbine information	On/off shore	Rotor diameter (m)	Hub height (m)	Wind speed (m/s)
[4]	1997	Denmark	c	33.3		1500	20	38.4		I/O	CMO	3 blades	off	64	55	17
[4]	1997	Denmark	o	50.0	15.9	400	20	22.8		PA	M(O)					
[4]	1998	Argentina	c	5.9	42	2.5	20	22		PA	CMT(O)					
[4]	1998	Argentina	c	8.3	29	30	20	22		PA	CMT(O)					
[4]	1998	Argentina	c	12.5	18	225	20	22		PA	CMT(O)					
[4]	1998	Germany	o	23.8		500	20	29.6		PA	CGMOT	3 blades		40.3	44	
[4]	1998	Germany	o	15.4		500	20	29.6		I/O	CGMOT	3 blades		40.3	44	
[4]	1998	Germany	o	21.7		1500	20	31		PA	CGMOT	3 blades		66	67	
[4]	1998	Germany	o	14.1		1500	20	31		I/O	CGMOT	3 blades		66	67	
[4]	1999	Germany	c	26.3		1500	20	31		PA	CDGMOT			66	67	
[4]	1999	India	c	31.3		1500	20	45.9		PA	CDGMOT	E-66		66	67	
[21]	1999	USA	o	23.0	14.4	342.5	30	24		I/O	(B)CDMOT	Kenetech KVS-33	on	32.9	36.6	
[21]	1999	USA	o	17.0	20.2	600	20	31		I/O	(B)CDMOT	Tacke 600e	on	46.0	60.0	6.1
[21]	1999	USA	o	39.0	8.9	750	25	35		I/O	(B)CDMOT	Zond Z-46	on	46.0	48.5	
[4]	2000	Denmark	o	51.3	16.5	500	20	40	0.39		MTCGOD	3-blades	off	39	40.5	16
[4]	2000	Denmark	o	76.9	9.7	500	20	40	0.26		MTCGOD		on		41.5	
[22]	2000	Italy	o	7.7	36.15	2500				I/O	MCO					
[4]	2000	Belgium	o	30.3	9.2e	600	20	34.2		PA	DM(O)					
[4]	2000	Belgium	o	27.8	7.9e	600	20	34.2		I/O	DM(O)					
[4]	2001	Japan	o	6.3	39.4	100	25	34.8		I/O	CMT			30	30	
[4]	2001	Brazil	o	14.5		500	20	29.6		I/O	CGMOT	3 blades; E-40		40.3	44	
[23]	2002	USA	c	80.0	8.16e						TCO					
[24]	2003	Canada	c	123.5	10	500	20			PA	MCTOD					
[24]	2003	Canada	c	125.8	7.1	500	20			PA	MCTOD					
[24]	2003	Canada	c	109.6	3.7	500	20			PA	MCTOD					
[25]	2004	Germany	c	8.4	45	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	44	7.5
[25]	2004	Germany	c	7.8	48	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Germany	c	6.2	61	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Germany	c	4.7	81	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Germany	c	4.9	77	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	65	7.5
[25]	2004	Germany and Brazil	c	22.5	15	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	44	7.5
[25]	2004	Germany and Brazil	c	21.2	16	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Germany and Brazil	c	16.4	20	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Germany and Brazil	c	12.0	27	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Germany and Brazil	c	12.4	26	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	65	7.5
[25]	2004	Germany and Brazil	c	27.7	8	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	44	7.5
[25]	2004	Germany and Brazil	c	25.7	8	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Germany and Brazil	c	20.0	10	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Germany and Brazil	c	15.6	13	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Germany and Brazil	c	16.4	12	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	65	7.5
[25]	2004	Brazil	c	32.7	3	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	44	7.5
[25]	2004	Brazil	c	30.0	3	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Brazil	c	24.0	3	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Brazil	c	18.9	4	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Brazil	c	18.9	4	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	65	7.5
[25]	2004	Brazil	c	40.0	2	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	44	7.5

[25]	2004	Brazil	c	40.0	2	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Brazil	c	32.7	2	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Brazil	c	25.7	3	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	55	7.5
[25]	2004	Brazil	c	25.7	3	500				PA-I/O	MTCOD	Enercon E-40	on	40.3	65	7.5
[26]	2004	Germany	c	14.8		5000	20	50	0.33	PA	MTCOD	Repower Systems AG	off	126.5	95	9.2
[27]	2004	Germany	c	70.0		500	20		0.29	PA	MCTO	Enercon E-40	on	40.3	44	
[27]	2004	Germany	c	53.0		500	20		0.38	PA	MCTO	Enercon E-40	on	40.3	55	
[27]	2004	Germany	c	38.0		500	20		0.53	PA	MCTO	Enercon E-40	on	40.3	65	
[27]	2004	Germany	c	64.0		1500	20		0.32	PA	MCTO	Enercon E-66	on	66	67	
[27]	2004	Germany	c	50.0		1500	20		0.4	PA	MCTO	Enercon E-66	on	66	67	
[27]	2004	Germany	c	39.0		1500	20		0.52	PA	MCTO	Enercon E-66	on	66	67	
[28]	2005	Japan	c		29.5	300	30	20		PA-I/O	CMO					
[28]	2005	Japan	c		20.3	400	30	20		PA-I/O	CMO					
[29]	2006	Italy	o	19.2	14.8e	7260	20			I/O	MTCOD		on	50	55	
[30]	2006	Germany	c	30.0	10.2	1500					MTCOD					
[30]	2006	Germany	c	32.7	8.9	2500					MTCOD					
[30]	2006	Germany	c	29.4	10.2	1500					MCOTD		on			
[30]	2006	Germany	c	32.3	8.9	2500					MCOTD		off			

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 and maintence, D = Decommissioning, e = CO_2 equivalents including CH_4 and N_2O, ( ) = partly covered.

to significantly improve generation efficiency, and thus the EROI will remain fairly stable. Adding carbon sequestration technology to coal combustion will increase the energy cost of power generation. Hydropower has a relatively high EROI (about 12), but on a global scale it has a modest potential for expansion. The average EROI for hydropower is based on a literature review of published life cycle energy assessments ($N = 7$). Similar literature reviews were done for coal ($N = 12$), solar thermal ($N = 9$) and geothermal ($N = 11$) power generation systems.

The comparison with nuclear power is complicated by a number of factors. The system boundary looms large for nuclear power because the fuel cycle has many steps, and because many of the important stages are upstream (mining, milling, enrichment) or downstream (decommissioning, waste disposal) from the generation stage. The data presented in Fig. 3 are from Lenzen's [14] comprehensive survey of the life cycle energy and greenhouse gas emissions of nuclear energy based on 52 unique analyses. The complete sample yields an average EROI = 15.8, but with a very large standard deviation (28.0). The 52 studies exhibit a wide range in the number of stages that are assessed, which explains some of the huge variation in EROI. Most of the studies with EROI in the upper range shown in Fig. 3 exclude multiple stages of the fuel cycle, and thus generate unrealistically high EROI. Excluding those outliers produces an average EROI = 9.1, but still with a large standard deviation (8.0). Readers should also note that two-thirds of the analyses in Lenzen's nuclear review date from 1980 or earlier, and thus do not represent nuclear power plants currently being built, or any plants that will be built in the future. Suffice it to say that there remains significant uncertainty regarding the energy costs associated with nuclear power.

The EROI for wind is demonstrably higher then the current EROI for photovoltaic (PV) power generation. A literature ($N = 62$) review of LCAs and net energy assessments for PV systems from 1997 through 2007 produced an average EROI of about 6.5 (s.d. = 4.7). The vast majority of these studies were simulations that assumed specific lifetimes, locations, module efficiencies, solar intensities, and other operating characteristics. Like the wind and nuclear analyses, the PV studies exhibit a wide range in terms of scope, with decommissioning and recycling stages often excluded. *Ceteris paribus*, the ongoing improvements in PV module efficiency will tend to improve the EROI over time.

5.3. *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. These issues have been discussed in detail elsewhere, and are summarized here:

- The dramatic cost reductions in the manufacture of new wind turbines that has characterized the past two decades may be slowing [15] due to a variety of economic, financial, and technical reasons. Recently this is particularly true in light of the rising energy and commodity prices, which are slowly escalating turbine costs. The rising global demand for turbines is also driving prices upward.
- The uncontrolled, intermittent nature of wind poses unique challenges to grid management relative to operator-controlled (baseload) resources such as coal, gas, or nuclear generation [16].
- Much of the wind resource base is located in remote locations, so costs exist in getting wind-generated electricity from the local point-of-generation to a potentially distant load center.

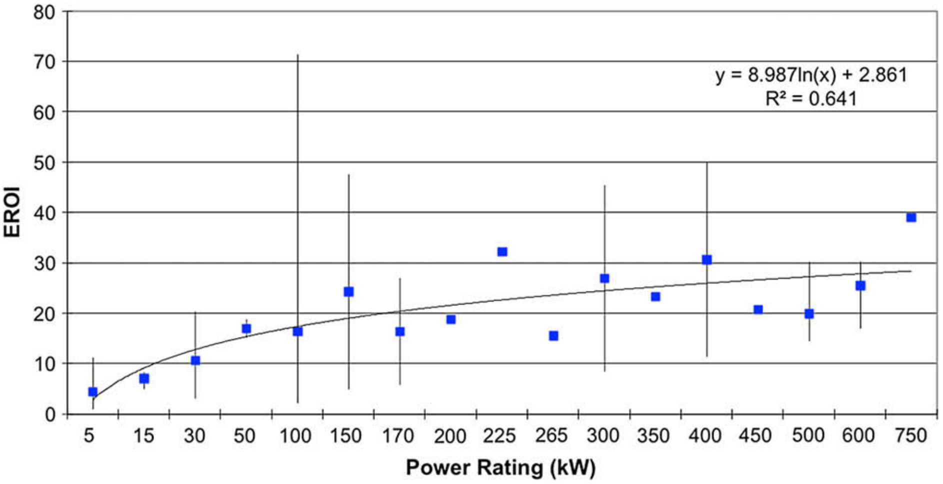

Fig. 3. EROI for operational wind turbines below 1 MW as a function of power rating in kilowatts.

- The remoteness of the wind resource base also generates increased costs 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). Little is known about the extent of these costs.
- At about 6 or 7 MW per square kilometer of net power potential, wind plants are necessarily spread-out over a significant land area [17]. Thus, wind plants must compete with alternative uses of these land resources. This is especially true when the land is a significant source of aesthetic and/or recreational value.
- Government subsidies have spurred the development of wind energy [18]. But subsidies are always subject to political whims, and thus constitute a significant issue 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 [19]. Considerable additional research on operational wind facilities is required to provide a comprehensive assessment of the potential magnitude of these risks.

None of these challenges are necessarily insurmountable. Indeed, some of them may be relatively modest in cost terms when fully assessed. The point here is simply that an EROI is crucial but is not independently a sufficient condition for the continued widespread expansion of wind energy.

5.4. Difficulties in calculating EROI

Our analysis illustrates the longstanding observation that EROI is sensitive to the choice of system boundaries [10,20]. Studies using the input–output analysis have an average EROI of 12 while those using process analysis an average EROI of 24. Process analysis typically involves a greater degree of subjective decisions by the analyst in regard to system boundaries, and may be prone to the exclusion of certain indirect costs compared to input–output analysis [10].

Operational wind turbines offer the best opportunity to calculate real EROI, as concrete data for input and output parameters can be used. However, practical obstacles interfere with data availability. For example, data retrieval related to turbine transport or construction material/volume becomes complicated by the involvement of multiple contractors, inconsistencies in record keeping, and other factors. Additionally, wind turbine developers or owners/operators may be unwilling to provide data due to confidentiality and competitive restrictions (this is especially true for production data), or the time required to collect information. These

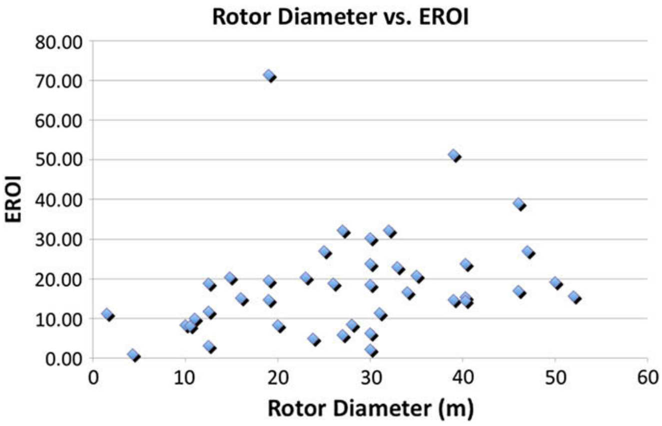

Fig. 4. EROI for operational wind turbines below 1 MW as a function of rotor diameter in meters.

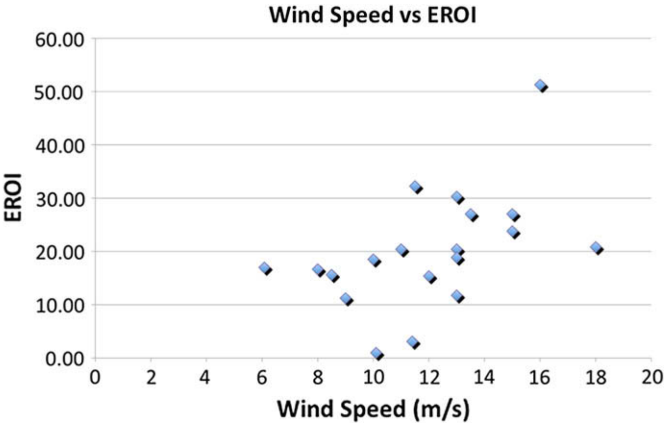

Fig. 5. EROI for operational wind turbines below 1 MW as a function of wind speed in meters per second.

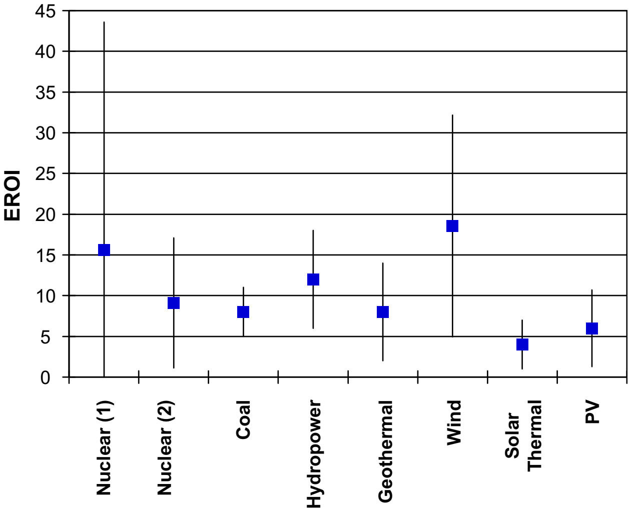

Fig. 6. EROI for power generation systems. Nuclear (1) represents the average and standard deviation for the entire sample of analyses reviewed by Lenzen [14]. Nuclear (2) omits the extreme outliers from Lenzen's survey, and thus represents a better assessment of what the EROI for nuclear is likely to be. See text for description of further sources.

constraints give rise to the need for estimation, which increases the level of uncertainty even for operational turbines.

6. Conclusions

This analysis reviews the extant literature on the net energy return from wind energy systems, ranging in date from 1977 to 2007. Our survey shows average EROI for all studies (operational and conceptual) of 25.2 ($n = 114$; std. dev = 22.3). The average EROI for just the operational studies is 19.8 ($n = 60$; std. dev = 13.7). This places wind in a favorable position relative to other forms of power generation, and suggests that wind energy could yield significant economic and social benefits relative to other power generation systems. Ongoing technical progress in wind energy technology will undoubtedly lead to further energy cost reductions. However technical progress and a high EROI are not sufficient conditions for the continued rapid expansion of wind energy. A number of social, economic, environmental and regulatory issues need resolution.

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