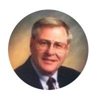
Emissions and Energy Efficiency Assessment of Baseload Wind Energy Systems

ARTICLE *in* ENVIRONMENTAL SCIENCE AND TECHNOLOGY · APRIL 2005

Impact Factor: 5.33 · DOI: 10.1021/es049946p · Source: PubMed

3 AUTHORS:

Paul Denholm
National Renewable Energy Laboratory



G.L. Kulcinski
University of Wisconsin–Madison

Tracey Holloway
University of Wisconsin–Madison

Environ. Sci. Technol. **2005**, *39*, 1903–1911

Emissions and Energy Efficiency Assessment of Baseload Wind Energy Systems

PAUL DENHOLM*

1500 Engineering Drive, University of Wisconsin–Madison, Madison, Wisconsin 53706

GERALD L. KULCINSKI

439 Engineering Research Building, 1500 Engineering Drive, University of Wisconsin–Madison, Madison, Wisconsin 53706

TRACEY HOLLOWAY

Center for Sustainability and the Global Environment (SAGE), 1710 University Avenue, University of Wisconsin–Madison, Madison, Wisconsin 53726

The combination of wind energy generation and energy storage can produce a source of electricity that is functionally equivalent to a baseload coal or nuclear power plant. A model was developed to assess the technical and environmental performance of baseload wind energy systems using compressed air energy storage. The analysis examined several systems that could be operated in the midwestern United States under a variety of operating conditions. The systems can produce substantially more energy than is required from fossil or other primary sources to construct and operate them. By operation at a capacity factor of 80%, each evaluated system achieves an effective primary energy efficiency of at least five times greater than the most efficient fossil combustion technology, with greenhouse gas emission rates less than 20% of the least emitting fossil technology currently available. Life-cycle emission rates of NO_X and SO_2 are also significantly lower than fossil-based systems.

Introduction

Baseload power plants generate electricity at nearly constant power, providing a high capacity factor, output stability, and reliability. As a result, baseload plants are responsible for producing a large fraction of the electricity generated in the United States. Coal, nuclear fuels, and natural gas fuel the majority of these plants (*1*). Baseload plants that use these fuel sources have a number of unfavorable characteristics. Coal-fired plants deplete fossil fuel resources and produce greenhouse gases (GHGs), sulfur dioxide, and nitrogen oxides. Natural gas plants also produce harmful air emissions and draw on finite natural gas resources. Nuclear plants produce radioactive waste products and present risk of accidents and weapons proliferation. These concerns have caused many to seek alternative power sources that can provide the same capacity factor, output stability, and reliability of conventional baseload plants.

Wind energy alone cannot meet these requirements. When wind energy is combined with energy storage, however, it becomes a viable alternative, providing a source of power that may be functionally equivalent to a conventional baseload plant. The creation of baseload wind energy systems using wind generation and storage can increase the economic penetration of wind energy far beyond the 10–20% levels commonly quoted (*2*). In addition, baseload wind energy systems are easily integrated into power systems with limited operational flexibility, such as those that lack a significant amount of fast-responding gas and hydroelectric generation. These types of power systems are common in the midwestern United States, an area with excellent wind resources (*3*).

The declining cost of wind energy has now made baseload wind energy systems economically feasible, increasing the possibility of large-scale integration into the United States' electric power system (*2*). For this reason, it is important to examine the environmental impacts of combined wind generation and energy storage systems. Inclusion of energy storage with wind energy generation also allows for a more equitable comparison between intermittent wind generation and conventional generation technologies.

A realistic assessment of baseload wind systems must include an economically viable energy storage system as well as consideration of other effects such as transmission requirements. This study developed a baseload wind model using wind turbine, storage, and transmission technologies that are considered economically viable in the midwestern United States when deployed on a large scale. The model uses energy storage to increase the capacity factor of a typical wind generator (25–45%) to a baseload level (greater than 70%) (*4*) and increase the output stability and reliability of wind energy as well. Capacity factor is defined as the average plant output divided by the maximum possible output over a period of time, generally one year.

The development of the model was strongly influenced by the constraints of electricity transmission, which ultimately establishes the maximum output of the wind system. Since new transmission development will be required to deliver wind energy from remote locations in the midwestern United States to major load centers, a high system capacity factor is required to maximize the use of these expensive transmission assets (*5*). The model was designed to produce an amount of power that is equal to, but does not exceed, a level established by the transmission capacity. The effects of losses in the transmission system were also considered in the model.

Life cycle analysis tools were applied to examine several major environmental performance indicators: energy intensity and emission rates of GHGs, sulfur dioxide (SO_2), and nitrogen oxides (NO_X).

Modeling Baseload Wind Energy Systems

Several studies of baseload wind energy systems have been published, primarily to evaluate the economic performance of such systems (*5*–*7*). This study developed a model of a baseload wind system to perform an energy and environmental performance analysis. The wind energy storage (WES) model uses a spreadsheet format (Microsoft Excel) and simulates the hourly performance of a wind farm integrated with energy storage. On the basis of wind energy data and input parameters including storage efficiency and capacity, the WES model calculates the number of wind turbines and other infrastructure required to deliver performance similar to traditional baseload sources. The model compares the wind farm output to the target output on an hourly basis and attempts to provide constant power output by storing, or releasing from storage, the appropriate amount of energy. The objective of the WES model is to maximize the use of limited, capital-intensive transmission capacity to provide a

* Corresponding author present address: National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401; phone: (303)384-7488; fax: (303)384-7449; e-mail: paul_denholm@nrel.gov.

10.1021/es049946p CCC: $30.25
Published on Web 01/21/2005

constant amount of baseload power equal to the size of the transmission system.

Wind-Farm Data. Modeling the performance of a baseload wind energy system requires wind turbine power output data that captures the short-term and long-term variations in wind speed. This study used hourly wind turbine data from a number of locations to estimate performance over a range of wind resources. Each case used data taken over one full year to consider seasonal variations in wind speed.

Hourly power output from existing wind farms and individual turbines was used to create five data sets that simulate the performance of larger wind farms. Three data sets were derived from hourly power output from existing midwestern United States wind power plants, provided by the National Renewable Energy Laboratory (*8*). Two additional data sets were derived from existing single wind turbine sites in North Dakota (*9*). Data from the single turbines was modified to consider energy losses that would occur in larger wind farms from transmission losses and array losses that occur in turbines situated downwind from neighboring turbines. Additional details about the creation of hourly power output data sets are provided in the Supporting Information. The capacity factor for these existing wind turbine systems ranged from 33.1 to 37.3%. Since existing wind farms for which long term data is available use smaller, less efficient turbines than are currently being deployed, these cases likely represent the lower limit of system performance for new baseload wind systems located in the midwestern United States.

It is also desirable to estimate the performance of a large wind farm using state-of-the-art turbine technology. Since a full year of hourly output data from very large wind farms using the latest turbine technology does not yet exist, hourly power data for this case was simulated. Details regarding the simulation of the data set are provided in the supplemental appendix. The net average capacity factor for the simulated wind turbine array is 46.3%.

This set of six hourly power output data formed the basis to simulate baseload wind power plants.

Storage System. Many technologies exist that are capable of storing electrical energy, including pumped hydro storage, batteries, and hydrogen. Compressed air energy storage (CAES) is significantly less expensive (by at least 50%) than other utility scale storage systems and suitable for very large scale storage of wind energy in the midwestern United States (*10,11*). The use of CAES for wind energy storage has been proposed or is being pursued in two locations in the United States (*12,13*).

CAES systems are based on conventional gas turbine technology and utilize the elastic potential energy of compressed air. Energy is stored by compressing air in an airtight underground storage cavern. To extract stored energy, compressed air is drawn from the storage vessel, heated, and then expanded through a high-pressure turbine, which captures some of the energy in the compressed air. The air is then mixed with fuel and combusted, with the exhaust expanded through a low-pressure gas turbine. The turbines are connected to an electrical generator. Turbine exhaust heat and gas burners are used to preheat cavern air entering the turbines.

CAES can be considered a hybrid generation/storage system because it requires combustion in the gas turbine. The storage benefit of precompressed air is the elimination of the turbine input compressor stage, which uses approximately 60% of the mechanical energy produced by a standard combustion turbine. By utilization of precompressed air, CAES effectively "stores" the mechanical energy that would be required to turn the input compressor and uses nearly all of the turbine mechanical energy to drive the electric generator. The performance of CAES for this analysis is based on a study by Denholm and Kulcinski (*14*) and includes the effect of transmission losses between the wind farm and the CAES system. For this study, 1 kWh of electricity generated by the CAES turbine requires 4649 kJ of fuel plus 0.735 kWh of compressor electricity.

A large-scale CAES system requires an underground storage cavern in a salt dome, aquifer, or other geologic formation. Prior studies have found suitable geology for CAES in many parts of the midwestern United States (*15*). The size of the cavern in this study is measured in terms of the number of hours the CAES turbine can run at full output. Actual storage size would be dictated by economic and geological constraints. The base results reported in this study assume a CAES system with a total storage time of 24 h at full load, with the effects of different storage times also considered.

Wind-Farm/Storage System Model. The hourly wind-farm output was placed into the WES model, which is designed to produce an output that resembles the nearly constant output of a baseload coal or nuclear plant. An overview of the WES system model follows, with a more detailed description provided in the supplemental appendix.

At each hour, the wind power output is compared to the constant "target" output power. If the wind power exceeds the target, energy is placed into storage, and if wind power is below the target, energy is withdrawn from storage.

Large seasonal variations in wind speedd and limits on the size of the storage vessel will result in nonconstant output as well as unusable wind energy generation. This issue is illustrated in Figure 1, a sample profiles of a 2-week period for one possible wind−CAES operating scenario.

In this case, the constant target output is set to 900 MW. Much of the time this goal is met from the combination of wind energy transmitted directly or wind energy that is stored. However, on several occasions, insufficient storage results in wind energy production that cannot be stored. This "spilled" energy results in decreased economic and environmental performance. The amount of spilled energy can be reduced by raising the constant target output as illustrated in Figure 2. In this case, the target output is set to 1100 MW, which reduces the amount of spilled energy. However, raising the target output increases the amount of time the system "underproduces", which decreases the system capacity factorr and its economic value to an electric power system.

Since wind energy spill rate (% of total wind energy spilled) and capacity factor are generally proportional in a baseload wind system, a real system would need to be optimized considering geographic and temporal economic conditions. Figure 3 shows the wind energy spill rate as a function of system operating capacity factor for the six evaluated cases using a storage time of 24 h. The gray lines show performance of the five cases that use data from existing wind farms. The dark lines show results from the simulated case. All of the existing wind farms can achieve capacity factors greater than 70% with spill rates under 10%, while the simulated case can achieve greater than an 80% capacity factor with a 10% spill rate. Limits to system capacity factor can be placed in context of conventional generation. Given the appropriate level of demand, top performing coal or nuclear plants can achieve a 90−95% capacity factor, while lower values more common (*16*).

This limitation can be largely mitigated with longer storage times. Figure 4 illustrates the spill rate as a function of storage time for different capacity factors using data from the simulated case. Figure 4 assumes the storage and transmission system are 100% reliable. With sufficiently long storage times, a capacity factor of 90% or more can be achieved with relatively low spill rates. Additional discussion of the effects of storage time on system operation is provided in the Supporting Information.

As a result of these various factors, no single value should be reported for the operational performance of a baseload

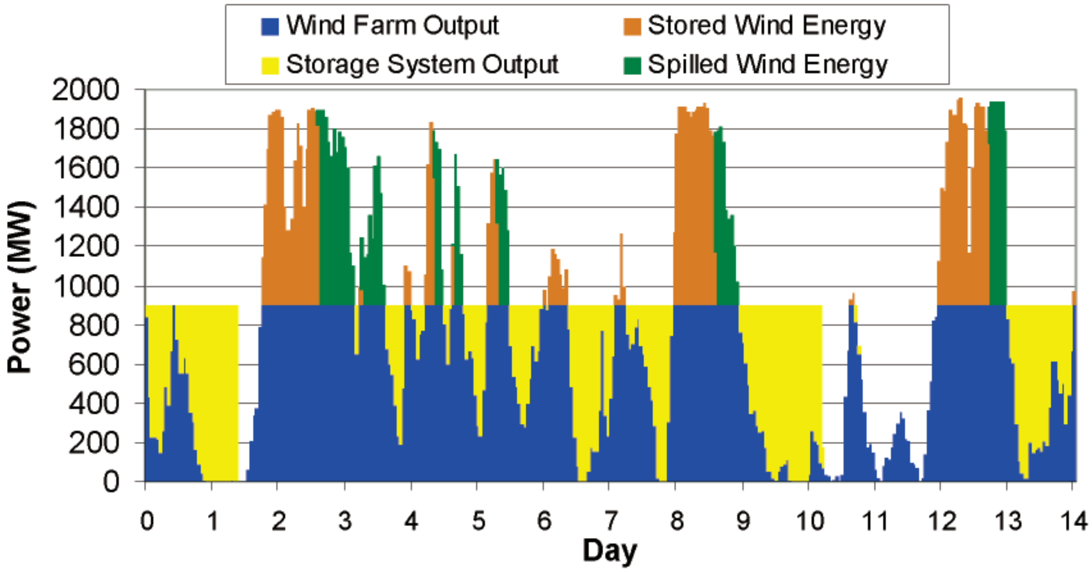


FIGURE 1. Sample baseload wind generator output (target output = 900 MW).

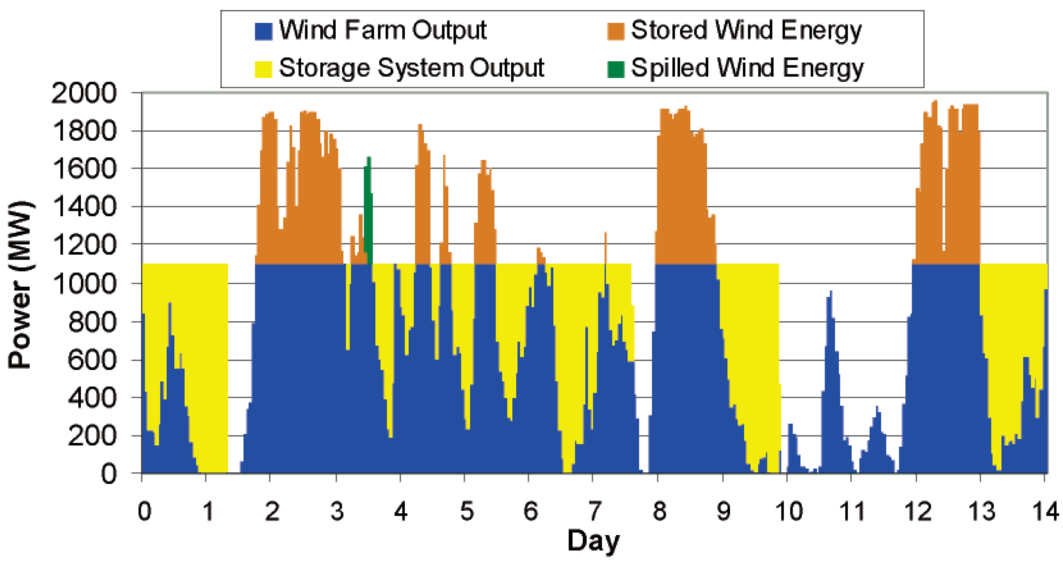


FIGURE 2. Sample baseload wind generator output (target output = 1100 MW).

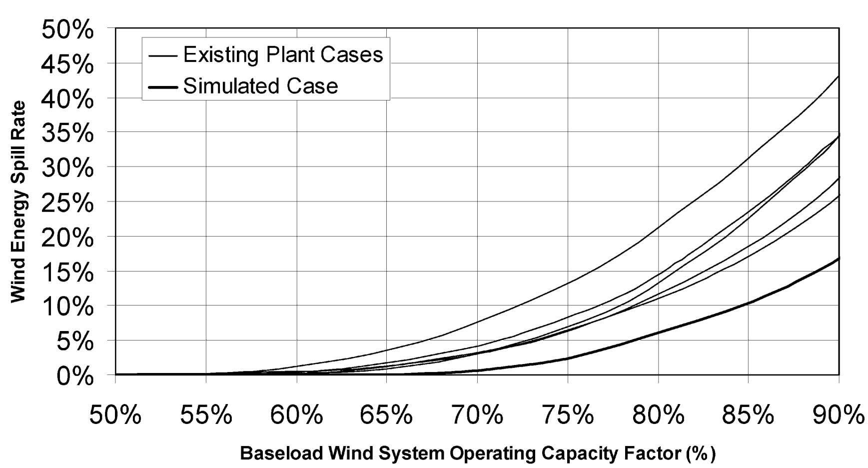


FIGURE 3. Spill rate vs operating capacity factor for the various baseload wind cases.

wind system. The results of this analysis are provided by a set of curves that represent a likely performance envelope for modern wind energy systems coupled with CAES energy storage over a range of capacity factors. The WES model evaluated these plants over a capacity factor range from 50%, where no energy was spilled, to 90%, where spill rates would likely be considered uneconomic for many of the cases. However, results are generally reported for the baseload

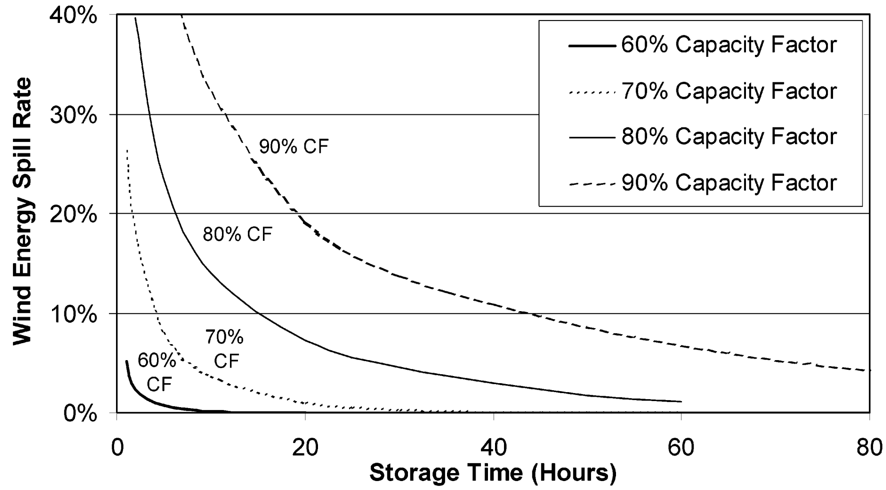


FIGURE 4. Wind energy spill rate as a function of storage time for the simulated 1 000-MW baseload wind system.

operating regime, defined as a capacity factor range of 70–90%.

The six wind farm data sets were used to evaluate the performance of two types of baseload power plants. The data sets from the five existing plants were used to analyze baseload plants of approximately 300 MW, using a 24-h storage time in each case.

The simulated data set was used to create a large baseload plant of about 1 000 MW. This plant could serve a significant fraction of the baseload energy demand of a large load center. This plant would likely be coupled to an expensive, very long distance transmission line which would motivate very high capacity factors. To enable increased capacity factors with lower spill rates, the system was evaluated with a 50-h storage time in addition to the base 24-h storage time.

Transmission Loss Effects. The effects of long-distance transmission were also considered in the WES model. It is likely that wind energy will often be transmitted over longer distances than electricity generated by traditional sources, and new transmission development will be required to deliver baseload wind energy to load centers. Both conventional alternating current (AC) and high voltage direct current (HVDC) lines may be used to deliver baseload wind energy. HVDC is economically superior to conventional AC lines when the transmission distance exceeds a certain threshold, currently estimated at 500–800 km (*17*).

To evaluate the effect of transmission losses, two transmission systems are considered. The five smaller 300-MW systems assume transmission over a 300 km, 345 kV AC system, while the simulated 1 000-MW case uses a 1 200 km, ±500 kV HVDC system. The transmission loss rate, L_T, is estimated at 3% for the AC line and 9% for the HVDC line (*18*). Losses in the transmission system require an increase in the system size to produce a desired output. This multiplier effect can be written as

$$\text{installed power capacity (MW)} = \frac{\text{delivered power capacity (MW)}}{1 - L_T} \qquad (1)$$

This multiplier effect increases both the system size (power) and the required input energy (such as CAES fuel).

Model Results. The WES model provides a number of technical performance indicators that may be used to evaluate each system's environmental performance. The two most important factors are the peak power ratio and the system fuel consumption rate.

The peak power ratio represents the number of units of wind turbine power capacity required to deliver 1 unit of constant power to the transmission network. For a baseload wind energy system operating at a capacity factor of 100% with an ideal storage system (100% efficient and unlimited capacity), the peak power ratio would be the reciprocal of the wind farm capacity factor. (A wind farm operating at a capacity factor of 33% would require 3 MW of turbines for an average output of 1 MW). A wind energy system using a pure storage system such as pumped hydro would require a greater peak power ratio to compensate for storage inefficiencies, which are reflected in a storage energy ratio (defined as kWh_{in}/kWh_{out}) greater than 1. Limits to the storage system capacity will also increase the peak power ratio since some of the energy generated will be spilled. Using the hybrid CAES system reduces the peak power ratio since wind energy generation is supplemented by the electricity effectively generated by natural gas combustion. The use of CAES therefore represents a tradeoff between reduced wind turbine requirements and increased fossil fuel usage.

Figure 5 illustrates the peak power ratio as a function of system capacity factor for the various cases. The simulated case shows a much lower peak power ratio than the existing wind turbines, a result of the substantially increased turbine capacity factor. The 50-h storage time slightly reduces the peak power ratio for the simulated case, since reduced spill energy reduces turbine capacity requirements.

Figure 6 illustrates the system fuel consumption rate, or heat rate, defined as the CAES fuel energy input per unit of total system output, excluding transmission effects. For systems operating at a capacity factor from 70 to 90%, the heat rate ranges from roughly 680–1 250 kJ/kWh and can be compared to a traditional fossil plant heat rate, which is typically 7 000–12 000 kJ/kWh (*19*). The heat rate is essentially a function of how much energy must be stored. The system heat rate, divided by the constant CAES heat rate (4 649 kJ/kWh) (*16*) is the fraction of electricity ultimately provided by the storage system, which ranges from 15 to 27% for the cases operating in the 70–90% capacity factor range.

The high wind turbine capacity factor in the simulated case results in a relatively small amount of stored energy at lower system capacity factors, which explains its lower heat rate. Lower spill rates tend to increase the system heat rate, illustrated by the 50-h storage case, where more energy is placed into storage, resulting in slightly greater fuel use.

Environmental Assessment

Life-cycle analysis methods were used to assess several indicators of environmental performance of the baseload wind energy systems. Life-cycle analysis accounts for the complete environmental impacts of a product over its life,

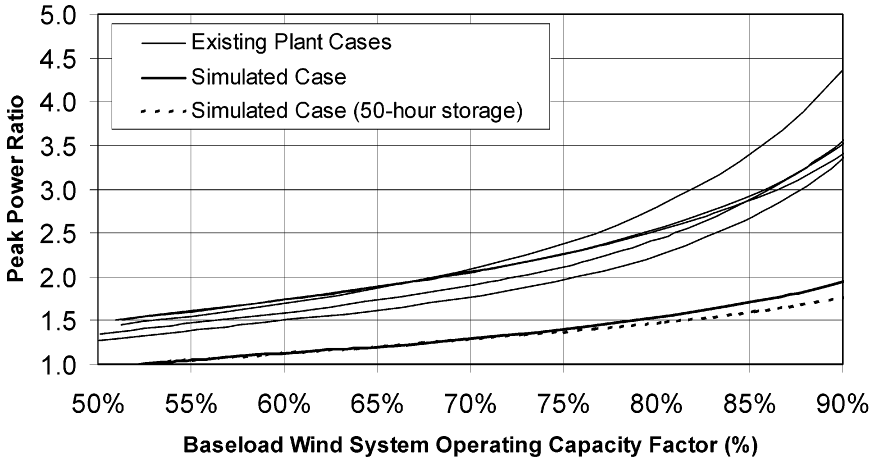


FIGURE 5. Peak power ratio vs operating capacity factor for the various baseload wind cases.

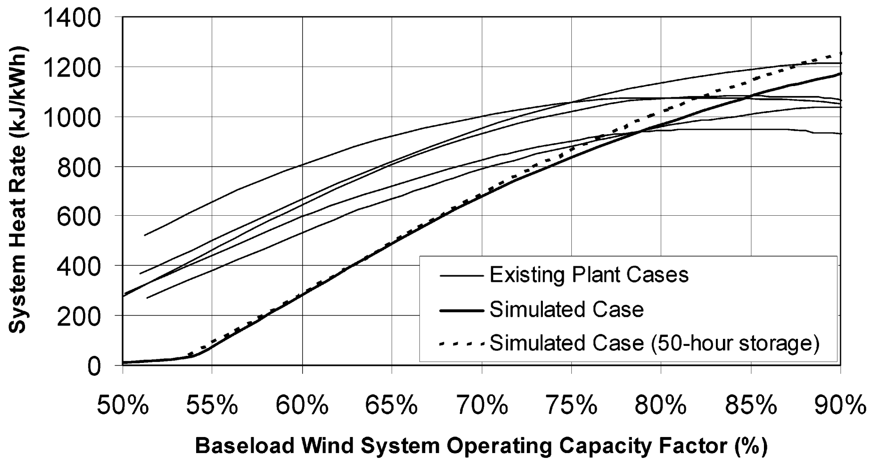


FIGURE 6. System heat rate vs operating capacity factor for the various baseload wind cases.

including manufacturing, operation, and disposal (*20*). The analysis performed does not include a comprehensive life-cycle impact assessment but focuses on several of the most significant concerns regarding production of electricity from conventional baseload sources, particularly fossil fuels. The environmental performance indicators analyzed include primary energy use and emission rates of GHGs, SO_2, and NO_X.

Primary Energy Efficiency. Environmental impact is often proportional to energy use, so a commonly used general environmental performance indictor is energy intensity, or primary energy used per unit of product output.

The inverse of energy intensity is commonly used to express the life-cycle net energy yield, or primary energy efficiency, of electric power systems

$$\text{primary energy efficiency (\%)} = \frac{\text{electrical energy output (MWh)}}{\text{primary energy input (MWh)}} \quad (2)$$

If all the primary energy in eq 2 is derived from fossil thermal energy, the primary energy efficiency is equivalent to the life-cycle fossil fuel efficiency, expressed as

$$\text{fossil fuel efficiency (\%)} = \frac{\text{electrical energy output (MWh)}}{\text{fossil energy input (MWh}_t\text{)}} \quad (3)$$

Life-cycle fossil fuel efficiency is a potentially more useful comparative metric of environmental impact and energy resource sustainability. For energy systems in the United States, the primary energy efficiency is approximately equal to the fossil fuel efficiency since fossil fuels account for about 85% of the total energy used in the United States (*16*). This measure is also appropriate considering a major input into the wind/CAES system is natural gas fuel.

The primary energy efficiency of a conventional fossil source is typically less than 50% and is limited by thermal conversion processes and fuel delivery requirements. For example, a combined-cycle gas turbine with a plant thermal efficiency of 50% has a primary energy efficiency of about 42%, mostly due to losses in the fuel delivery system (*21*). The net life-cycle energy efficiency of renewable energy systems may be substantially greater than 100%, since their primary energy requirements are typically much less than their production of electrical energy. A renewable energy system with a primary energy efficiency greater that 100% (equal to a net energy yield greater than 1) may be referred to as a renewable breeder.

A renewable energy system could have a primary energy efficiency of less than 100% and still be superior to a fossil system in terms of energy resource sustainability. A unit of natural gas energy that produces 0.42 units of electrical energy from a combustion system could alternately be used to construct a wind energy system that, over its lifetime, delivers 0.9 units of electrical energy. In this case, the renewable system produces less energy than is required to construct it, yet it still produces more than twice the amount of electrical energy than would be extracted by combustion. This example illustrates the counterintuitive result that a renewable energy system that consumes more energy than it produces is not unreasonable.

The energy requirements for electricity produced by a baseload wind system originate from three major sources: construction and disposal of the various facilities, CAES fuel consumption, and other system operation and maintenance (O&M).

The energy related to plant construction and decommissioning may be expressed as the total construction-related primary energy, EE_P (kWh_t), divided by the lifetime output of the storage plant E_L (kWh_e). The life of the plant is assumed to be 20 years. Energy for CAES fuel is reflected by the effective fuel consumption rate, or heat rate (HR_{eff}), of the entire system (typically measured as kJ_t/kWh_e but normalized to (kWh_t/kWh_e). Other O&M energy requirements are reflected in EE_{op} (kWh_t/kWh_e) and include requirements such as transportation fuel for site personnel, operation of CAES emissions control equipment, and the construction and installation of replacement parts.

The total life-cycle primary energy efficiency η_L (kJ_e/kJ_t) for the baseload wind system can be expressed as

$$\eta_L = \frac{1}{HR_{eff} + EE_{op} + \frac{EE_P}{E_L}} \qquad (4)$$

All energy intensity metrics, including primary energy efficiency, are only general indicators of environmental performance. They treat all primary energy uniformly and do not assign a qualitative or quantitative difference between various energy sources such as coal and natural gas, which have substantially different impacts per unit energy consumed. In addition, primary energy efficiency ignores the energy content of renewable energy sources such as wind. When used as a comparative metric of environmental impact, this assumes no opportunity costs or environmental harm resulting from the extraction of wind energy. Opportunity costs include the reduced value of the wind energy downwind from individual turbines, although some of this opportunity cost is captured in the array losses. Environmental impacts associated with the extraction of wind energy include aesthetic impacts, bird kills (*22*), and possible effects on local climate (*23*). Additional, more specific metrics must be used to compare these and other impacts.

Emissions of GHGs, NO_X, and SO_2. The GHGs are a major concern regarding production of electricity from conventional baseload sources. While wind turbines produce no GHG emissions during normal operation, current reliance on fossil fuels for manufacturing and transportation result in emissions from turbine construction, installation, and maintenance. In addition, CAES fuel combustion is a potentially significant source of GHG emissions.

In addition to CO_2, other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) may be released during the entire fuel cycle of an electric power system. The total greenhouse gas emission rate is measured in terms of the total global warming potential (GWP) of all emitted greenhouse gases, normalized to carbon dioxide mass equivalents (*24*).

The life-cycle GHG emission rate from electricity produced by the baseload wind/CAES system is calculated in a manner similar to the life-cycle efficiency. Life-cycle emissions related to plant construction and decommissioning may be expressed as the total construction-related emissions, EM (g CO_2 eq), divided by the lifetime electrical output of the system, E_L (kWh). Emissions related to the CAES fuel consumption are a function of the system fuel consumption rate (HR_{eff}) and the emissions factor for the CAES fuel, EF_{gas} (g CO_2 eq/kJ). Emissions related to wind and storage plant O&M are given by EF_{op} (g CO_2 eq/kWh). The complete life-cycle emissions factor, EF_L (g CO_2 eq/kWh), is then defined as

$$EF_L = (HR_{eff}EF_{gas}) + EF_{op} + \left(\frac{EM}{E_L}\right) \qquad (5)$$

Another concern regarding the production of electricity from baseload fossil sources is the emission of SO_2 and NO_X. Emissions of these substances lead to acidification and production of fine particulates that impair respiratory function and visibility (*25*). NO_X emissions also can increase formation of ground level ozone. While SO_2 is typically associated with combustion of coal and high-sulfur fuel oil, NO_X is produced by all fossil fuel combustion.

The life cycle emissions rates of SO_2 and NO_X may be calculated using eq 5, where GHG emission factors are replaced with those for the desired pollutant.

Analysis of System Components and Operation. A process-based life-cycle analysis was performed on each component of the baseload wind energy system to estimate energy use and resulting emissions from construction and operation.

The total energy requirements and emissions from the construction and operation of wind turbines were based on previous studies of modern, large turbines (*26,27*). The results of each study were normalized to derive a total amount of energy used for the construction and operation of 1 MW of large wind turbines over a 20-year lifetime. The mean value of the nine studies used was 9 830 GJ/MW, with a large spread from 7 430 to 13 882 GJ/MW. This range of results is due to a variety of methodological differences between studies as well as the types of turbines and location of manufacture. A comprehensive discussion of these issues is provided by Lenzen and Munksgaard (*26*). The impact of this range of turbine energy intensities and emission rates is discussed in section 5.

Life-cycle energy requirements and emissions related to CAES are derived from an existing study (*14*). Upstream components of natural gas fuel production and delivery and pipeline construction are included. Production and transmission of natural gas is energy intensive and can result in considerable emissions of GHGs, SO_2, and NO_X (*21*).

In addition to the effects of transmission losses, energy consumption and emissions associated with construction of the two transmission systems is considered (*18*). The assessment for the HVDC line used in the simulated case includes the AC/DC converter stations. In addition to emissions from transmission line construction, emissions from biomass losses in rights-of-way were also considered. This assessment assumes that 25% of the transmission line area requires removal of trees, which are assumed to be a mix of typical midwestern United States species (*28*). Right-of-way widths are assumed to be 37 m for the AC system and 50 m for the HVDC system (*18*), with net carbon emissions of about 6 kg/m^2 of transmission line right-of-way.

Results of the individual component analysis are reported in Table 1. From these data, the environmental performance of a baseload wind system can be calculated, given the appropriate sizing and system operation data. Emissions and energy requirements for reservoir recharging from external sources during low wind periods are not considered. This is justified given the relatively high capacity factor of the system, which is comparable to a conventional baseload plant. The net emissions reported for most conventional systems include only emissions during operation. For example, the net emissions from nuclear and coal-fired power plants do not include emissions from other sources that replace their output during refueling or maintenance outages.

Results

Table 2 summarizes the results of the environmental analysis of the baseload wind systems for the likely operating regimes, defined as operating capacity factors between 70 and 90%. Also included in the table are results from previous studies

TABLE 1. Environmental Parameters for Baseload Wind System Construction and Operation

component and description	parameters included	primary energy requirements	GHG emissions (CO_2 eq)	SO_2 emissions	NO_X emissions
wind turbine (1 MW of turbine capacity)	construction, O&M, decommissioning	9.83 TJ_t	792 tonnes	850 kg	1 890 kg
CAES system (1 MW of CAES capacity, 24 h of storage)	construction, nonfuel O&M, decommissioning, gas pipeline	8.22 TJ_t	587 tonnes	710 kg	1 580 kg
AC transmission line (300 MW, 300 km)	construction, O&M, biomass losses	413 TJ_t	96.2 k tonnes	35.5 tonnes	79.4 tonnes
HVDC transmission line (1 GW, 1 200 km)	construction, O&M, biomass losses	3 659 TJ_t	568.7 k tonnes	315.3 tonnes	704.6 tonnes
CAES system fuel combustion (generation of 1 kWh of electricity from CAES turbine)	combustion of natural gas fuel	4 649 kJ_t	234 g	0.001 g	0.057 g
natural gas delivery (delivery of natural gas for 1 kWh of CAES generation)	gas production and processing, pipeline and compressor operation	518 kJ_t	51 g	0.13 g	0.23 g

TABLE 2. Life-Cycle Environmental Parameters for Baseload Wind Systems Operating at a 70−90% Capacity Factor Compared to Other Baseload Generation Technologies

environmental parameter	primary energy efficiency (%)	GHG emission rate (g CO_2 eq/ kWh)	SO_2 emission rate (g/kWh)	NO_X emission rate (g/kWh)
Baseload Wind Systems				
range for 5 existing turbine cases	208-312	69-102	~0.05	~0.1
simulated case (24 h storage)	214-336	66-99	~0.05	~0.1
simulated case (50 h storage)	203-321	67-104	~0.05	~0.1
Other Baseload Energy Systems				
wind (no storage, CF range ~25-50%)	1540-4350	5-25	<0.02	<0.1
nuclear fission	25-35[a]	10-25	<0.05	<0.1
natural gas combined-cycle	40-45	400-500	0.1-0.4	0.2-0.6
coal (typical U.S.)	28-32	900-1100	2-10	2-4
coal (supercritical with SO_2 and NO_X controls)	32-38	850-1000	0.5-1	0.3-2

[a] Includes energy content of uranium fuel. Values typically exceed 1 500% if fuel content is excluded.

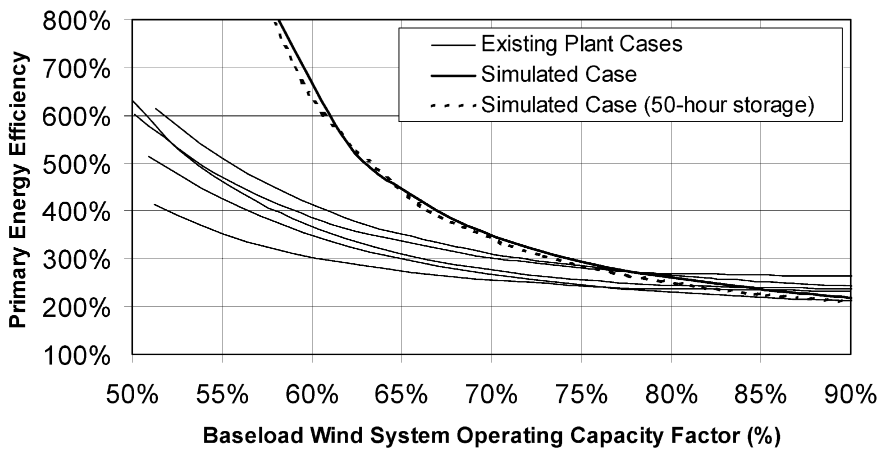


FIGURE 7. Life-cycle primary energy efficiency vs operating capacity factor for the various baseload wind cases.

of baseload electric power systems including coal, natural gas combined cycle, nuclear fission, and wind used without storage (*21*,*26*,*29*,*30*).

Primary Energy Efficiency. Figure 7 provides the range of results for the primary energy efficiency analysis of the various cases. All evaluated cases demonstrate primary energy efficiencies greater than 100%, which is superior to any fossil-fuel-based system. In the baseload operating regime, the least efficient wind/storage system evaluated produces greater than 4 times more electricity per unit of primary energy input than a highly efficient combined-cycle gas turbine.

Figure 8 illustrates the distribution of primary energy inputs for a delivered unit of electrical energy from the simulated case, operating at a capacity factor of 80%. Transmission losses are listed as a separate category, although the energy associated with these losses is ultimately derived proportionally from the other sources listed. Taking into account transmission losses, CAES fuel input represents 85% of input energy requirements when considering both the fuel and fuel delivery in this case.

Emissions of GHGs, NO_X, and SO_2. Figure 9 provides the range of greenhouse gas emission rates for the six evaluated cases. Operating at a capacity factor between 70 and 90%, the evaluated cases produce a net GHG emission rate of 66−104 g CO_2 eq/kWh. This rate is higher than the life-cycle emission rate of wind energy without storage or nuclear generated electricity but is substantially lower than any fossil technology. The GHG emission rate from a baseload wind plant is about 10% that of typical coal plants, which provide a large fraction of the baseload electricity in the upper midwestern United States (*16*).

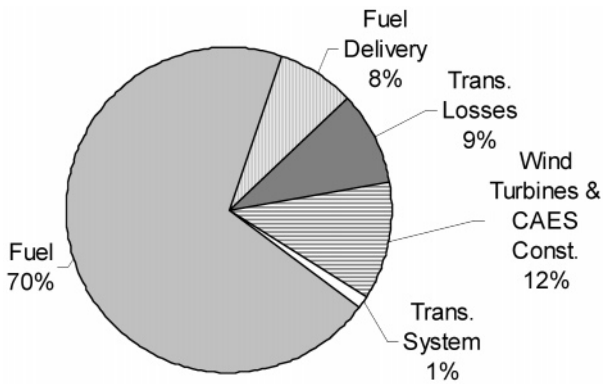


FIGURE 8. Distribution of energy sources for the simulated 1 000-MW baseload wind system operating at an 80% capacity factor.

The dominant source of GHG emissions from the wind/CAES system is natural gas combustion, as illustrated in Figure 10, the distribution of GHG emissions from the simulated operating at an 80% capacity factor. As can be expected, the distribution of sources is similar to Figure 8, since there is a general relationship between energy use and GHG emissions. The large share from transmission construction is largely due to biomass losses. Methane leaks result in a higher contribution of GHG emissions from natural gas transmission, due in part to the high GWP of CH_4 (21 times that of CO_2).

Life-cycle production of SO_2 and NO_X from the baseload wind system is a small fraction of those from fossil-based systems. About 60−70% of the SO_2 emissions are from the production and transmission of natural gas, with most of the remainder from upstream manufacturing processes. Similarly, a large fraction (around 50%) of NO_X emissions are from natural gas production and transmission. NO_X emissions from CAES combustion produces only about 20% of the life-cycle NO_X emissions, in part due to the use of selective catalytic reduction of NO_X in the CAES turbines.

Discussion

The creation of baseload wind energy systems utilizing energy storage will be necessary for wind energy to capture a large share of the electrical energy supply in the United States. CAES is capable of providing large scale, economic energy storage for wind energy in the midwestern United States. The combination of wind, storage, and transmission produces a baseload energy system that provides an alternative to conventional baseload power, currently dominated by fossil and nuclear systems.

Increasing the capacity factor of wind energy systems to baseload performance through the use of CAES results in a substantial decrease in their environmental performance, as illustrated in Figures 7 and 9. As the system capacity factor is increased, the natural gas consumption rate increases, as a result of the increased level of storage utilization. This results in lower primary energy efficiency, and a higher air emission rate, particularly of greenhouse gases. The increased spill rate at higher capacity factor also decreases the environmental performance, although this impact is small. Despite this decrease in environmental performance, high system capacity factors are generally desirable from a system perspective. As the capacity factor of the wind system is increased, the system will likely displace a larger amount of fossil generated electricity, which provides greater overall environmental benefits, as the life-cycle emissions rate and fuel efficiency of a very high capacity factor wind system are significantly better than any fossil generator.

Figures 8 and 10 shows that system fossil fuel efficiency and GHG emissions are relatively insensitive to the parameters related to system construction and O&M. The wide range of energy intensities for turbine manufacturing has little impact on the efficiency of the entire system, particularly when operating at higher capacity factors. For the simulated case operating in baseload regime, the maximum change in primary energy efficiency due to variation in turbine manufacturing energy is less than 4%. GHG emissions are similarly insensitive to construction energy intensity. A 50% reduction in GHG intensity for all system construction, transportation, and maintenance results in a maximum life-cycle GHG emission reduction of about 13% for plants operating in the baseload regime. The combustion of natural gas establishes the lower limit for GHG emissions from a baseload wind system, and if all upstream energy from construction and operation were derived from emission-free sources, the net emissions from the baseload wind system would approach a lower limit of approximately 49−89 g CO_2 eq/kWh resulting from CAES combustion.

Cleaner fuel mixes could reduce the life-cycle emission rates of SO_2 and NO_X that result from upstream manufacturing by up to about 40%. The lower limit for SO_2 and NO_X emissions are based on the production and use of natural gas fuel. Further reductions in emissions of SO_2 and NO_X are dependent on reduction of emissions in upstream gas processing.

Beyond a cleaner production fuel mix, additional increases in environmental performance would require a change in the storage system, such as an increase in the CAES turbine efficiency. Use of a storage system that does not require fossil fuels could dramatically decrease the primary energy use

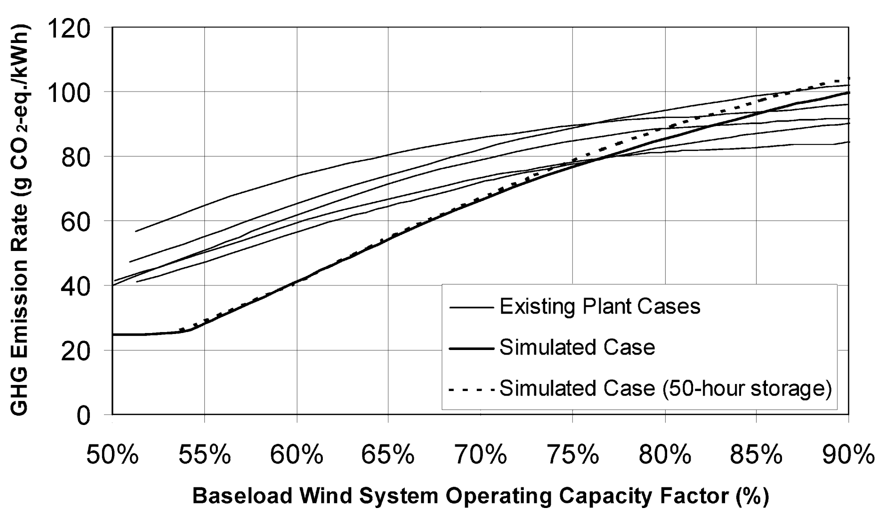


FIGURE 9. System GHG emission rate vs operating capacity factor for the various baseload wind cases.

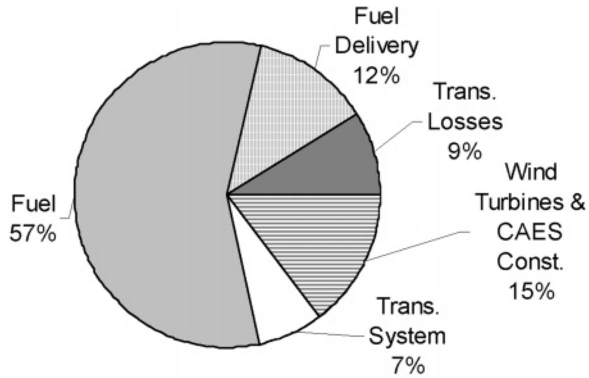


FIGURE 10. Distribution of GHG emissions sources for the simulated 1 000-MW baseload wind system operating at an 80% capacity factor.

and air emissions. An alternative, fossil-independent wind/CAES system could burn renewably generated hydrogen, although this is probably uneconomic based on the current cost of electrolytic hydrogen (*31*). Biofuels are another alternative to natural gas for the CAES system, if CAES remains economically superior to advanced batteries or other forms of electrical energy storage.

Additional considerations remain for a more comprehensive evaluation of the environmental impacts of baseload wind systems. In addition to aesthetic concerns and other wind turbine specific issues, more analysis is needed to examine the system-wide interaction between wind turbine generation, energy storage, and conventional generation. A baseload wind system integrated into a larger utility system will interact with conventional thermal generation in a manner that may alter the overall environmental performance of the individual generation components. A system-wide analysis of a utility system incorporating both thermal generation and baseload wind generation would provide additional insight into the potential emission reductions and other environmental benefits of deploying wind generation with energy storage.

Acknowledgments

The study was supported in part by the Energy Center of Wisconsin, the University of Wisconsin—Madison and the U.S. Department of Energy. Discussions with Paul P. H. Wilson and Paul J. Meier provided considerable assistance in the preparation of this study. Data provided by Yih-Huei Wan at the National Renewable Energy Laboratory is gratefully acknowledged.

Supporting Information Available

Additional details about the WES model, including the wind resource, operation of the energy storage system, and the interaction of the wind turbine generation and storage system. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) U.S. Department of Energy. *Annual Energy Review 2002*. Energy Information Administration: Washington, DC, 2003.
(2) Office of Utility Technologies, Energy Efficiency and Renewable Energy and Electric Power Research Institute. *Renewable energy technology characterizations*. United States Department of Energy: Washington DC, 1997.
(3) U.S. Department of Energy. *Electric Power Annual 2001*. Energy Information Administration: Washington, DC, 2002.
(4) Cassedy, E. S.; Grossman, P. Z. *Introduction to Energy*; Cambridge University Press: Cambridge, UK, 1998.
(5) Cavallo, A. J. High-capacity factor wind energy systems. *J. Solar Energy Eng.* **1995**, *117*, 137−143.
(6) Cavallo, A. J. Transforming intermittent wind energy to a baseload power supply economically. *Proceedings of the American Power Conferences*; Chicago, IL. 1997
(7) DeCarolis, J.; Keith, D. W. Is the answer to climate change blowing in the wind*? Proceedings of the first International Doctoral Consortium on Technology, Policy, and Management*; Delft University: Delft, The Netherlands, 2002.
(8) Wan, Y. National Renewable Energy Laboratory: Golden, CO, unpublished results.
(9) Minnkota Power Cooperatives. http://www.minnkota.com/infinity.htm. 2003.
(10) Cavallo, A. J. Energy storage technologies for utility scale intermittent renewable energy systems. *J. Solar Energy Eng.* **2001**, *123*, 387−389.
(11) Schoenung S. M. *Characteristics and technologies for long- vs short-term energy storage*; Sandia National Laboratories: Albuquerque, NM, 2001.
(12) Iowa Stored Energy Project. Via http://www.idea.iastate.edu/isep/index.asp. Accessed March 4, 2004.
(13) Desai, N.; Nelson, S.; Garza, S.; Pemberton, D.; Lewis, D.; Reid, W.; Lacasse, S.; Spencer, R.; Manning, L. M.; Wilson, R. *Study of Electric Transmission in Conjunction with Energy Storage Technology*. Texas State Energy Conservation Office. 2003.
(14) Denholm, P.; Kulcinski, G. L. Life cycle energy requirements and greenhouse gas emissions from large-scale energy storage systems. *Energy Convers. Manage.* **2004**, *45*, 2153−2172.
(15) Mehta, B. CAES geology. *EPRI Journal*. October/November 1992: 38−41.
(16) U.S. Department of Energy. *Annual Energy Outlook 2003*. Energy Information Administration: Washington, DC, 2003.
(17) *Final Environmental Impact Statement Arrowhead − Weston Electric Transmission Line Project − Volume 1*. Public Service Commission of Wisconsin, 2000.
(18) Denholm, P.; Kulcinski, G. L. *Life Cycle Greenhouse Gas Emissions Related to the Transmission and Distribution of Electricity in Wisconsin*. Energy Center of Wisconsin: Madison, WI, 2003.
(19) Elliot, T. C., Chen, K.; Swanekemp, R. C. *Standard Handbook of Powerplant Engineering*; McGraw-Hill: London, 1998.
(20) Curran, M. A. *Environmental life-cycle assessment*; McGraw-Hill: New York, 1996.
(21) Spath, P. L.; Mann, M. K. *Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System*; National Renewable Energy Laboratory: Golden, CO, 2000.
(22) Erickson, W. P.; Johnson, G. D.; Strickland, M. D.; Young, D. P.; Sernka K. J.; Good, R. E. *Avian Collisions with Wind Turbines: A Summary of Existing Studies and Comparisons to Other Sources of Avian Collision Mortality in the United States*; National Wind Coordinating Committee: Washington, DC, 2001.
(23) Keith, D. W.; DeCarolis, J. F.; Denkenberger, D. C.; Lenschow, D. H.; Malyshev, S. L.; Pacala, S.; Rasch, P. J. The influence of large-scale wind-power on global climate. *Proc. Natl. Acad. Sci. U.S.A.* **2004**, *101* (46), 16115−16120.
(24) Guinee, J. B.; Gorree, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; De Koning, A.; Van Oers, L.; Sleeswijk, A. W.; Suh, S.; Udo de Haes, H. A. *Handbook on Life Cycle Assessment. Operation Guide to the ISO Standards*; Kluwer Academic Publishers: Dordrecht, 2002.
(25) U.S. Department of Energy. *Electricity Generation and Environmental Externalities: Case Studies*; Energy Information Administration: Washington, DC, 1995.
(26) Lenzena, M.; Munksgaardb, J. Energy and CO_2 life-cycle analyses of wind turbines—review and applications. *Renew. Energy* **2002**, *26*, 339−362.
(27) White, S. W.; Kulcinski, G. L. Birth to death analysis of the energy payback ratio and CO_2 gas emission rates from coal, fission, wind, and DT fusion electrical power plants. *Fusion Eng. Des.* **2000**, *48* (248), 473−481.
(28) U. S. Environmental Protection Agency. *Inventory of U. S. Greenhouse Gas Emissions and Sinks: 1990−2000*. Washington, DC, 2001.
(29) Spath, P. L.; Mann, M. K.; Kerr, D. R. *Life Cycle Assessment of Coal-fired Power Production*. National Renewable Energy Laboratory: Golden, Colorado. 1999.
(30) Meier, P. J.; Wilson, P.; Kulcinski, G. L.; Denholm, P. U. S. Electric industry response to carbon constraint: a life-cycle assessment of supply side alternatives. *Energy Pol.*, in press.
(31) Padró, C. E. G.; Putsche, V. *Survey of the Economics of Hydrogen Technologies*; National Renewable Energy Laboratory: Golden, Colorado, 1999.

Received for review January 9, 2004. Revised manuscript received November 28, 2004. Accepted December 2, 2004.

ES049946P