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Improving the technical, environmental and social performance of wind energy systems using biomass-based energy storage

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Abstract

A completely renewable baseload electricity generation system is proposed by combining wind energy, compressed air energy storage, and biomass gasification. This system can eliminate problems associated with wind intermittency and provide a source of electrical energy functionally equivalent to a large fossil or nuclear power plant. Compressed air energy storage (CAES) can be economically deployed in the Midwestern US, an area with significant low-cost wind resources. CAES systems require a combustible fuel, typically natural gas, which results in fuel price risk and greenhouse gas emissions. Replacing natural gas with synfuel derived from biomass gasification eliminates the use of fossil fuels, virtually eliminating net CO_2 emissions from the system. In addition, by deriving energy completely from farm sources, this type of system may reduce some opposition to long distance transmission lines in rural areas, which may be an obstacle to large-scale wind deployment.
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1. Introduction

Greatly expanded use of wind energy has been proposed to reduce dependence on fossil and nuclear fuels for electricity generation. The large-scale deployment of wind energy is

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limited by its intermittent output and the remote location of high value wind resources, particularly in the US.

Wind energy systems that combine wind turbine generation with energy storage and long distance transmission may overcome these obstacles and provide a source of power that is functionally equivalent to a conventional baseload electric power plant. A 'baseload wind' system can produce a stable, reliable output that can replace a conventional fossil or nuclear baseload plant, instead of merely supplementing its output. This type of system could provide a large fraction of a region's electricity demand, far beyond the 10–20% often suggested as an economic upper limit for conventional wind generation deployed without storage [1]. (It should be noted that the maximum penetration of wind into systems without storage is an area of considerable ongoing research [2].)

While energy storage and long distance transmission greatly increase the technical performance of wind energy these 'enabling' technologies may reduce its environmental benefits and social acceptability. The majority of existing utility-scale energy storage in the US and worldwide is pumped hydro storage (PHS), which requires two large bodies of water separated by a large difference in height [3]. In the Midwestern US, which contains a large percentage of the nation's low-cost wind resources, flat terrain, and lack of water makes compressed air energy storage (CAES) more suitable for new wind energy storage projects [4–6]. CAES is a hybrid storage/generation technology that requires combustible fuel (typically natural gas). This dependence on fossil fuels will compromise some of the environmental advantages of a baseload wind system. In addition, the need for new, high capacity, long distance transmission systems will decrease the social acceptability of this energy source, presenting barriers to its implementation.

A more socially and environmentally acceptable alternative is a baseload wind system that uses biomass fuel in the storage system instead of natural gas. This completely renewable energy system will decrease the system's dependence on fossil fuels, and may increase the acceptability of long distance transmission systems in agricultural regions by using farm-derived fuel sources.

2. Description of the standard baseload wind system

The basic components of a baseload wind system include a large amount of wind generation, a large-scale energy storage system, and long distance transmission. Cavallo [7–9] has performed a number of analyses that describe the basic technical characteristics and economic viability of baseload wind energy systems. More recent studies include economic analysis by DeCarolis and Keith [10] and Greenblatt [11], as well as an environmental assessment by Denholm et al. [12]. These previous studies assume that the wind/CAES system acts as a 'baseload' plant with nearly constant output. Actual power plant operation, however, will likely use the energy storage system to reduce low-value output during off-peak periods and increase high-value output during on-peak periods, improving the economics of the system [6]. This method of operation has been suggested for a proposed wind/CAES plant in Iowa [13], which will be the first plant built that incorporates the basic features of baseload wind systems described here.

A baseload wind system must incorporate a large-scale energy storage system capable of quickly responding to the variations of wind turbine generation. Compressed air energy storage (CAES) is a hybrid generation/storage technology well suited for this application. CAES systems are based on conventional gas turbine technology and utilize the elastic potential energy of compressed air [6,14]. Energy is stored by compressing air in an airtight underground storage cavern. To extract the stored energy, compressed air is drawn from the storage vessel, heated, and then expanded through a high-pressure turbine that 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.

CAES is considered a hybrid generation/storage system because it requires combustion in the gas turbine. Natural gas is used in existing CAES plants in Alabama [15] and Germany [16], and planned for use in proposed CAES plants in Ohio [17], Texas [18], and Iowa [13]. While it may be possible to use CAES without fuel combustion [14], this concept has not been demonstrated on any scale, while the combustion-based CAES systems in Germany and Alabama have been in operation since 1978 and 1991, respectively. A modern CAES system operating in isolation consumes about 0.7 kW h of electricity and 4500 kJ of fuel for each kW h delivered [3].

A large-scale CAES system requires an underground storage cavern in a salt dome, aquifer, or other geologic formation. Both existing CAES facilities use solution-mined salt caverns, while the proposed Iowa Stored Energy Project [13] will use an aquifer. Prior studies have found suitable geology for CAES in many parts of the Midwestern US [4,19]. Typical CAES systems operate with an air storage pressure range of 50–80 bar and require 200–300 m^3 per effective stored MW h [6,14,17]. Leak rates in both hard rock formations and salt domes have been evaluated and found to be negligible [14,20]. This study assumes that leak rates in aquifers would also be small enough to have minimal impact on technical or economic performance.

As part of a baseload wind system, CAES would be used to enable a nearly constant output by smoothing the highly variable output from wind turbine generation. The combination of roughly 1.5–3 MW of wind turbine generation operating at a capacity factor of 30–45% and 1 MW of CAES generation could produce a nearly constant 1 MW output [12]. When operating at a high capacity factor ($>75\%$), about 60–80% of the wind energy (averaged over a year) is placed directly onto the grid, while the remainder is stored (to be retrieved when the wind energy output falls below average) or 'spilled' (due to limits of the storage cavern and transmission capacity). A simplified schematic of a baseload wind system is illustrated in Fig. 1. The energy 'flow' of a baseload wind system is illustrated in Fig. 2, derived from an analysis by Denholm et al. [12]. The CAES performance values in Fig. 2 include the effects of transmission losses between the wind farm and the CAES facility [3].

Averaged over a year, the illustrated system would require a total fuel consumption of 800–1200 kJ per delivered kW h, depending on wind resources and system operation [12].

The high capacity factor of a baseload wind system will fully utilize expensive transmission capacity, which is essential if long, high capacity transmission systems are to link inexpensive wind resources with major load centers in the Midwestern US [8].

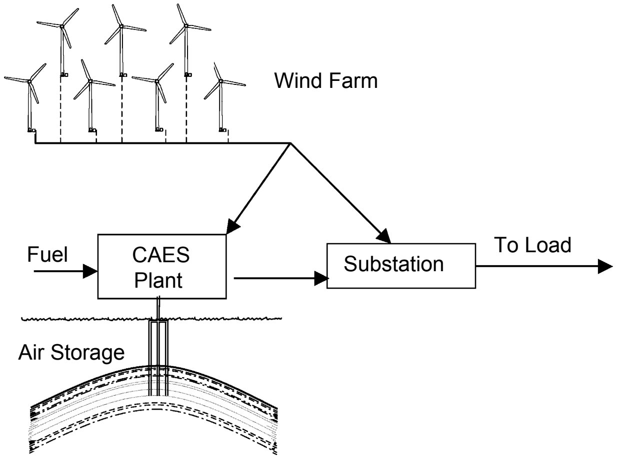

Fig. 1. Simplified schematic of a wind/CAES power plant.

3. Limitations of the standard baseload wind system

While a baseload wind system allows renewable wind energy to provide a direct substitute for a traditional fossil or nuclear generator, there are a number of limitations to this concept. One is the dependence of CAES on natural gas fuel and the associated issues of fuel price stability and greenhouse gas emissions. A second limitation is the likely opposition to new transmission lines in rural areas.

The natural gas consumption of a wind/CAES system is about 85% less than a combined cycle gas turbine generator operating at 50% thermal efficiency. Regardless, any continuous use of natural gas results in fuel price and supply risks and also results in emissions of greenhouse gasses. Because baseload energy sources typically require long-term contracts for both fuel and delivered electricity, both guaranteed fuel availability and predictable fuel costs are desirable. Natural gas fuel is subject to supply disruptions

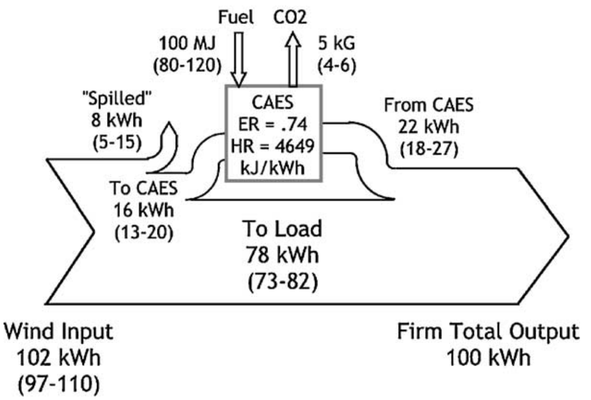

Fig. 2. Average energy flow through a typical baseload wind/CAES power plant.

and price spikes, which may decrease the attractiveness of the system to investors. The system's average consumption of 800–1200 kJ of natural gas per delivered kW h results in greenhouse gas emissions of 40–60 g/kW h [12]. (This value does not include the 'life-cycle' emissions associated with system construction, etc.) This value is much lower than any fossil-based system, however, the use of natural gas fuel may detract from the real and perceived environmental benefits of this type of system.

A potentially more significant disadvantage, which applies to any large-scale use of wind energy, is the need for long distance transmission between source and load. The type of line required by a baseload wind system may be particularly vulnerable to aggressive and costly opposition, because it requires a point-to-point line between generation and load, with few or no taps along the route. This means that unlike shorter lines, the long distance line provides little or no benefit to the population along its path.

Fig. 3 shows some of the major low-cost wind regions of the Midwestern US that could be tapped to deliver large amounts of electrical energy to major load centers. Also included are three hypothetical transmission lines (labeled 1–3) which are possible routes for baseload wind systems for Milwaukee and Chicago. These long distance lines will cross-primarily rural lands to serve the energy demands of distant urban load centers, while producing aesthetic impacts on residents who will derive little benefit from their presence. The transmission distances required in these three cases are in the range of about 750–1000 km. The long transmission distances required would likely result in the use of high voltage direct current (HVDC), which is considered more economic than conventional alternating current (AC) for transmission lines that exceed 600–800 km [21].

The Cooperative Power/United Power Association (CU) line, illustrated in Fig. 3, is one of only two long distance HVDC lines in the Midwestern US [23]. This line is designed to deliver low-cost lignite generated electricity 700 km from central North Dakota to eastern Minnesota [24].

The CU line illustrates the significant opposition that transmission line developers can face [24]. When the project was proposed in 1973, many farmers and residents in the line's

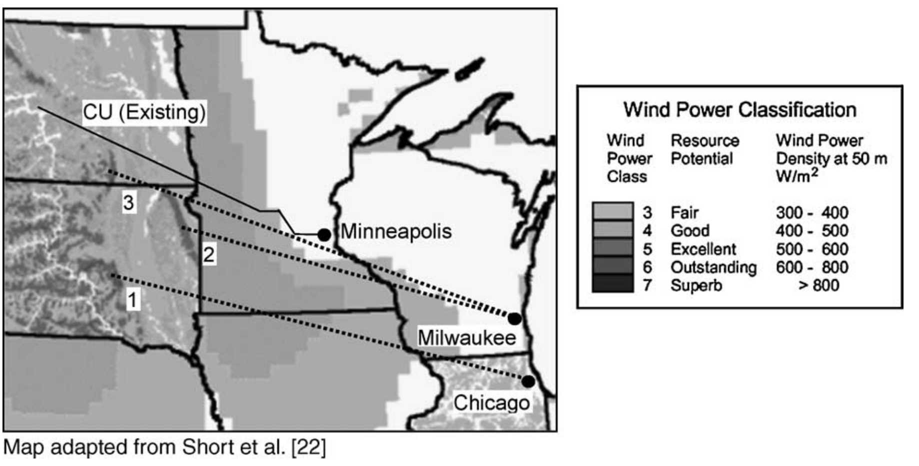

Fig. 3. Major wind resources in the upper Midwestern US and possible transmission routes.

path protested its aesthetic and other impacts. They also objected in principal to the imposition of the energy demands from a distant urban population on the rural landscape, and the lack of local control over regional development [24]. Legal challenges, protests, and appeals to local and state government officials led to significant delays, increased costs, and ultimately to increased restrictions on transmission line siting in the state of Minnesota [25]. Over 120 people were arrested during the protest actions. Most of the arrests were associated with civil disobedience and non-violent protest action, but there were several instances of violence against line surveyors and workers. Additional action was taken against the transmission line infrastructure. Saboteurs shot out thousands of line insulators and removed bolts from many of the towers, resulting in the collapse of at least 12 towers.

Actions taken against the development of the CU line may provide some indication of the future opposition to long distance point-to-point lines crossing rural areas of the Midwest. Even if the levels of protest action do not reach those experienced during the development of the CU line, significant costs and time delays associated with transmission line opposition may impede the development of baseload wind energy, leading utilities to seek cheaper alternatives which may ultimately be more harmful to the environment.

4. Advantages of a baseload wind system incorporating biofueled CAES

To eliminate the disadvantages associated with fossil fuel use in the CAES turbine and to reduce opposition to transmission line siting in agricultural areas, an alternative completely renewable baseload wind system is proposed. By replacing natural gas with farm-derived biomass fuel, the environmental and social limitations of the baseload wind concept may be substantially reduced. This alternative system also provides unique opportunities for the use of biofuels that might otherwise be unavailable.

Unlike fossil fuels, biomass crops are a renewable energy source, and can be largely carbon neutral over the entire cycle of harvest, combustion, and regeneration. Dedicated energy crops will provide a source of economic stability for both farmers and utilities, particularly when compared to natural gas. As a result, the use of biofuels in the CAES turbines reduces the net greenhouse gas emissions of the system, while potentially increasing overall price stability.

The use of biomass fuels in baseload wind systems has the potential to overcome some of the barriers to biomass-based electricity generation, including the high cost of fuel transport and remote location of low-cost biomass resources. Due to its low energy density, biomass is more expensive to transport than most fossil fuels. Like wind, biomass is a somewhat stranded resource, requiring long distance transmission lines between the resource and load. High transportation costs, and other land use restrictions are expected to limit the size of standard biomass power plants to below 200 MW [1], which is typically much smaller than desirable for the development of dedicated long distance transmission lines. Wind/CAES will require development of large, high-capacity transmission lines into regions with potentially stranded biomass resources. In many parts of the Midwestern US, such as western Iowa, western Minnesota, and the eastern Dakotas, there is a high coincidence of high-quality wind resources and the potential for relatively high-yield, low-cost biomass production [22,26]. The CAES system may be sited near the wind turbines and close to potential biofuel crop production. It is also possible that the CAES sites themselves may be somewhat dispersed, reducing biomass transport distances compared to a single large CAES site. The relatively low fuel requirements of the wind/CAES system (around 1000 kJ/kW h) increases the viability of biofuel use compared to standard combustion-based biomass energy systems.

Potentially more important could be the role of biofuel production in increasing the social acceptability of the transmission line, and the overall viability of the project. Unlike a point-to-point transmission line for a central generating station, or even a standard wind/CAES system, the development of a biofueled wind/CAES system brings potential economic benefits to some of the land owners along its path. Much of the land within economic transport distances to the CAES sites would likely be used to grow biofuel crops, including some of the transmission line corridors. Farmers who agree to transmission line right-of-ways could benefit from long-term purchase contracts, which may be necessary to guarantee availability of biomass fuel. This allows the transmission system to be a mechanism for export of farm products, making the farmer a stakeholder in the development and operation of the transmission system, akin to the development of a new road or rail line for crop shipments. This development of 'bioenergy corridors' would remove some of the potential conflict between land owners and transmission line developers. As a source of income stability for the region, the project may also gain support from agriculture lobbies and local elected officials.

The economic viability of biofuels decreases as the distance from the CAES facility increases. So while the integrated transmission line corridor/biofuel scheme proposed might provide some regional benefits, much of the line would have to be developed in a traditional manner. It is possible that the line associated with a biofueled baseload wind system may be looked upon more favorably than other large transmission lines, since the line will be used exclusively for the export of renewable, farm-based energy products.

5. Production of biofuels for CAES

The biofueled wind/CAES system will require reliable production of biomass-derived syngas and a CAES system capable of using syngas fuel.

A variety of biofuel crops have been evaluated for production in the Midwestern US. Among the promising candidates is switchgrass, a fast growing high-yield crop well suited to conditions in western Minnesota and the eastern Dakotas [26], areas with large amounts of low cost wind energy resources. Other possible biofuel crops suitable for this region include hybrid poplar and willow [26].

To provide a fuel suitable for use in the CAES turbine, solid biomass fuel must be dried and gasified through one of a variety of thermal gasification technologies in use or under development [27]. Thermal gasification describes the process of converting solid fuels such as coal or biomass into a syngas fuel that consists of a mixture of combustible gases including H_2, CO, CH_4, C_2H_4, and other minor constituents. Gasification of biomass for use in gas turbines has been demonstrated in a number of pilot programs but will likely require additional improvements in reliability before it can be deployed on the scale suggested in this work. A simplified schematic of a biomass gasifier is provided in Fig. 4

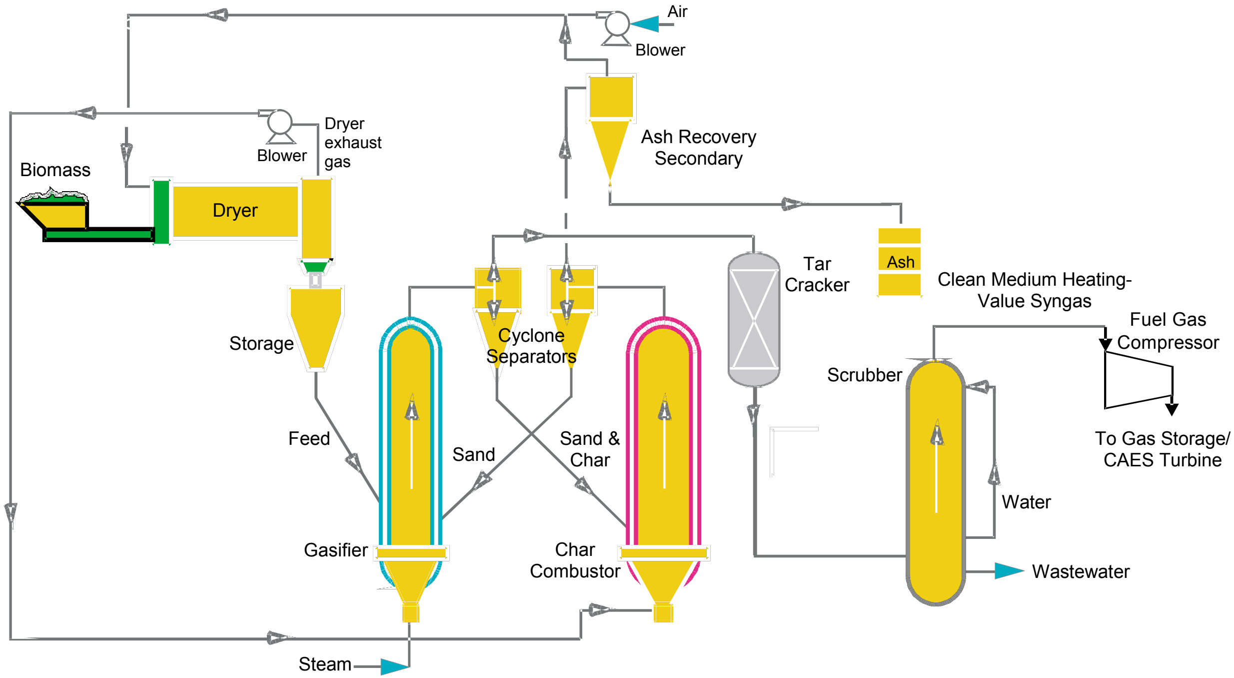

Fig. 4. Simplified schematic of a biomass gasification system.

[28]. No specific gasifier technology is assumed in this work. Instead a generic gasifier technology with an overall process efficiency of 65–75% ($MJ_{syngas}/MJ_{feedstock}$), is assumed [29,30]. This results in a feedstock requirement of 1.3–1.7 MJ of biomass input per MJ of delivered syngas fuel.

Although biomass-derived syngas fuel has never been used in a CAES turbine, several manufacturers have adapted standard gas turbines to run on a variety of biomass-derived syngas fuels [31,32]. Since a CAES turbine is essentially a standard gas turbine engine without an input compressor, it is likely that a CAES turbine could be adapted to operate on properly conditioned biomass syngas fuel.

The gasifier would probably be located at the CAES site to eliminate the need for syngas transport, and to maximize the integration of the CAES and gasification equipment. CAES produces low-grade waste heat in both the compression and combustion stages that might be used to dry raw biofuels and increase the gasifier efficiency.

Although gasification of dedicated energy crops is a likely candidate for large-scale integration with the wind CAES system, other biomass-based fuels, such as agricultural and animal waste and landfill gas are potential sources for the CAES turbines. The low fuel requirements of a baseload wind system increase the usefulness of some of these small scale fuel sources.

6. Crop land requirements for biofuel production

Biofueled baseload wind systems require significantly less land for crop production than traditional biomass generation systems, which may increase the viability of biomass as part of a large-scale electricity generation system.

Table 1 provides a summary of the cropland requirements for production of syngas from switchgrass for a biofueled baseload wind system. Yield estimates for switchgrass are based on production in the Midwestern US [26,33] and assume an energy content of 18.3 GJ/tonne.

From a land-use perspective, using biomass fuel to ‘firm up’ wind energy sources may be superior to more traditional biomass-only generation technologies. The most common biomass generation technology is co-firing in conventional coal-fired plants, where a fraction (typically, 2–10%) of the total fuel content of the system is replaced with biomass

Table 1
Cropland requirements for a biofueled baseload wind power plant

Component	Base case[a]	Estimated range
Average syngas fuel requirement (kJ/kW h)	1000	800–1200
Gasifier efficiency (%)	70	65–75
Switchgrass feedstock requirement (kJ/kW h)	1430	1070–1850
Switchgrass yield (tonne/ha per year)	11.3	9.1–12.5
Switchgrass yield (GJ/ha per year)	207	166–228
System cropland electricity yield (MW h/ha per year)	145.2	89.9–214.0
System cropland requirements (ha/GW h per year)	6.9	4.7–11.1

[a] Base case assumes the approximate mid point of estimates of system performance and switchgrass yields.

Table 2
Cropland requirements for biomass electricity generation

Generation technology	Biomass input heat rate (kJ/kW h)	Cropland use (m^2/MW h)	Cropland use ratio[a]
Biofueled wind/CAES	1430	69	1
BIGCC	10,000	482	7.0
Co-firing	11,250	542	7.9

[a] Ratio of cropland use for direct combustion to cropland use of biofueled wind/CAES for equal amounts of electricity generation.

[34]. The heat rate of such systems is typically in excess of 11,000 kJ/kW h. Higher performance can be derived from a biomass integrated gasification combined cycle (BIGCC plant), which combines a biomass gasifier and a combined cycle gas turbine generator. An estimate for the net efficiency of a BIGCC plant using a modern gasifier is 36%, requiring about 10,000 kJ of biomass input per net kW h [32].

Table 2 summarizes the biomass fuel requirements and land use associated with generating 1 kW h of completely renewable energy from three different biomass generation technologies. The values for biofueled wind/CAES are derived from the base case from Table 1, and do not include the land requirements for the wind generation system, which is considered in Section 7.

When considering potentially limited cropland availability, gasification of biomass for a wind/CAES system is superior to direct biomass generation. The direct combustion technologies require at least seven times more cropland to produce the same amount of electrical energy. In terms of power production, an amount of cropland capable of supporting 1000 MW of baseload wind can alternatively support less than 150 MW of generation from the direct combustion technologies.

7. Total land requirements for the biofueled baseload wind system

The land requirement for the wind turbines is another important consideration. Efficient capture of wind energy requires land surrounding the wind turbine to be unoccupied by tall structures or other wind turbines. The amount of unoccupied land surrounding each turbine is determined by the turbine array spacing. A standard turbine array spacing is 10 rotor diameters in the downwind direction and five rotor diameters in the crosswind direction, referred to as a 10D by 5D array [35]. Aesthetic effects may impact a greater area, but are not considered in this analysis. Table 3 shows the land requirements for several large turbines individually [36–39], and when deployed to produce a 1000 MW baseload wind/CAES plant achieving an 80% capacity factor and delivering 7008 GW h per year. The base case assumes a wind farm of 2000 MW, with a range of 1500–2500 MW, reflecting a range of wind conditions necessary to produce the desired constant 1000 MW output.

Using the base case biomass yield data from Table 1 produces a cropland requirement of 483 km^2 for a 1000 MW biofueled wind/CAES system operating at 80% capacity factor. This value is similar in scale to the base case land requirement for the wind farm

Table 3
Wind farm area requirements

Model	Max. output (MW)	Rotor diameter (m)	Individual turbine land area[a] (ha)	Individual turbine land area[a] (ha/MW)	Base case wind farm area (km^2)	Wind farm area range (km^2)
GE 1.5sl	1.5	77	29.6	19.8	395.3	296.5–494.1
GE 2.3	2.3	94	44.2	19.2	384.2	288.1–480.2
GE 2.5	2.5	88	38.7	15.5	309.8	232.3–387.2
GE 2.7	2.7	84	35.3	13.1	261.3	196.0–326.7
Vestas V80	2.0	80	32.0	16.0	320.0	240.0–400.0
Vestas V90	3.0	90	40.5	13.5	270.0	202.5–337.5

[a] Assuming 10D by 5D array.

component of the system (261–395 km^2). It is expected that a considerable amount of wind farm land will be coincident with biofuel crop production. If all of the available land in the wind farm were used to grow energy crops, an additional 92–226 km^2 of biofuel cropland would be required in the base case. A bioenergy corridor 1 km wide coincident with the first 100 km of the transmission line could provide a significant fraction of this additional land.

Table 3 does not include the relatively small amount of land that is displaced by the turbine foundations and access roads [40], and the CAES facility [17]. A modern wind farm using large (1.3–3.0 MW) wind turbines displaces about 1930 m^2/MW of turbine capacity, with the majority of that area occupied by turbine access roads [40]. For a 1000 MW wind/CAES system producing 7008 GW h/year, the total land actually occupied by all of the physical infrastructure is estimated at 2.9–4.8 km^2. This range of values is less than 2% of the land required by biofuel production.

8. System costs

The costs associated with natural gas fueled baseload wind/CAES systems have been previously evaluated. The delivered cost of electricity from the system can vary widely depending on wind resource assumptions and project financing. Table 4 provides a summary of two studies of natural gas fueled baseload wind systems. These cost estimates include the full cost of the CAES system including storage cavern preparation.

In both cases, the total cost is heavily dependant on the cost of wind energy generation, which is largely a function of turbine capital costs, financing rates, and wind resources. Effects of subsidies and tax credits are not considered in these results. These results can also be compared to estimates by DeCarolis and Keith [10], who found a cost of electricity (COE) from baseload wind systems of 5–7 cents/kW h over a variety of conditions. This range of results would tend to indicate that natural gas fueled wind/CAES may be competitive with other low emission technologies such as nuclear and coal gasification (especially if carbon capture and storage is required.)

Table 4
Previous analyzed cost of electricity delivered by a 'standard' baseload wind/CAES system

	Cavallo (1997) [9]	Greenblatt (2005) [11]
Turbine cost ($/kW)	700	700
Wind resource	440 W/m^2 at 50 m. 33.8% turbine capacity factor	Avg. wind speed = 8.2 m/s at 120 m. 35% turbine capacity factor
Base cost of wind generation (cents/kW h)	3.0–3.5	~3.8
CAES cost ($/kW)	560	890
Fuel cost ($/GJ)	4.3	4.7
Transmission line cost	41.3 M$ (200 MW AC, 240 km)	$315/kW (2000 MW, 750 km)
Annual capital charge rate (%)	10.7	11
Levelized COE (cents/kW h)	~4.7	~5.9
Fraction of cost from wind generation	64–74	~65

Greenblatt (2005) study assumes that the wind turbine cost and performance is achieved by 2020.

The biofueled baseload wind system described here will have lower or higher costs depending on three major factors: cost of biomass syngas fuel production and storage, cost of CAES turbines adapted to run on biofuels, and policy-driven costs associated with biofuel adoption.

The cost of syngas fuel can be compared to the cost of natural gas fuel for the CAES tubine. In 2003, the average cost of natural gas fuel delivered to US electric utilities was $5.16/GJ [41]. Since biomass-based syngas is not widely available, costs must be estimated based on projections of future large-scale biomass production and gasifier technology. The cost of syngas is a function of the cost of raw biomass fuel and the cost of biomass processing, which includes capital costs associated with gasification equipment, feedstock transport, energy required to convert solid biomass to gaseous form, and syngas storage.

Table 5 provides a range of costs for the production of biomass syngas. The table assumes syngas is derived from switchgrass grown in western Minnesota and the eastern Dakotas. The capital and operational cost of the gasifier is based on previous studies of the SilvaGas™ process developed by Battelle Columbus Laboratory and Future Energy Resources Corporation (FERCO) [29,30,32].

The base case estimates a delivered cost of biomass syngas fuel of about $6.9/GJ. Using an average fuel consumption rate of 1000 kJ/kW h for the wind/CAES system produces a fuel related cost of about 0.7 cents/kW h for the base case. This represents a cost increase of about 0.2 cents/kW h compared to a system fueled by natural gas with gas costs of $5.0/GJ. The range of syngas fuel-related costs compared to natural gas fuel at $5.0/GJ is negative 0.1 to positive 0.5 cents/kW h.

Modifications required to adapt the CAES turbine to run on syngas will also raise the cost of delivered electricity by a small amount. The capital cost of the CAES turbine is a relatively small fraction of total system costs [7], and if the cost of the biofueled CAES turbine is 25% more than a standard CAES turbine, the cost of electricity would increase by less than 0.1 cents/kW h.

Table 5
Estimated costs for delivered syngas fuel (all costs in \$/GJ)

Component	Base case[a]	Estimated range	Details/source
Feedstock (farmgate cost of dry switchgrass)	2.5	1.8–2.8	Base case cost of \$44.1 per tonne with a range of \$33.1–\$49.6 [26,33]. Energy content of 18.0 GJ (hhv) per tonne [26]
Transportation	0.6	0.2–1.4	Based on a cost of \$0.16/tonne km [42] over a range of 15–150 km
Gasifier system	1.4	1.0–1.9	Base case gasifier capital cost of \$83.8 per MJ/h of syngas capacity, with a cost range of \$56.9–\$106.1. Assumed annual capacity factor of 80% and capital recovery factor of 12%
Processing losses	1.3	0.7–2.2	Base case gasifier efficiency of 70% with a range of 65–75%
Operation and maintenance, storage	1.2	0.7–1.8	Storage cost based on compressed H_2 gas storage [43]
Total	6.9	4.3–10.1	

[a] Base case assumes the approximate mid point of estimates of various gasifier system costs.

Policy-driven economic factors will provide an additional difference in costs between the natural gas and biofueled systems. These can include the effects of subsidies for use of farm-derived products, improved financing available to renewable energy products, renewable energy project tax credits, or the impacts of carbon constraints. For example, US farmers currently receive subsidies for the production of ethanol fuel, in part to reduce the dependence on foreign sources of petroleum [44]. As the US becomes more dependent on imported natural gas [45], similar incentives may be put in place for farm-derived natural gas substitutes. In addition, the use of biofuels increases the renewable content of the delivered electricity, making it more eligible for production tax credits. Finally, a carbon tax of \$100/tonne carbon would add about 0.1–0.2 cents/kW h to the standard natural gas fueled wind/CAES system, which would be largely avoided in the biofueled CAES scenario.

Even without any of these policy driven reductions in cost, it appears that the use of biofuels in the CAES turbines would increase the total cost of the baseload wind system by significantly less than 1 cent/kW h. The costs associated with opposition to transmission line siting, instability of natural gas fuel price and availability, and environmental aspects of natural gas use may justify the biofueled alternative.

9. Implementation of a biofueled baseload wind system

The biofueled wind/CAES system concept described in this work represents a ‘second generation’ baseload wind system. First generation wind/CAES systems using natural gas fuel, such as the proposed Iowa Stored Energy Project, would demonstrate the basic compatibility between wind generation and CAES, and larger systems could follow, given the appropriate economic conditions and desire to move forward with low carbon electricity systems. Development of a biofueled CAES system will benefit from the lessons learned from the first generation of wind/CAES systems, as well as existing and future biomass gasifier systems.

The modular nature of CAES would allow a biofuel test program on a portion of a large CAES system without jeopardizing normal operation. For example, the proposed Norton CAES system consists of nine 300 MW turbines [17]. One of these turbines could be used to test biofuel operations without affecting the remaining eight turbines. Similarly, a future 1000 MW wind/CAES system might use four 250 MW turbines, one of which could be evaluated using biofuels. (The cost of a first-of-a-kind demonstration project would likely exceed the cost estimates previously calculated.) Once the basic biofuel technology is proven, utilities could explore cooperative transmission line and wind farm development with farmers in regions with economic wind and biomass resources.

10. Conclusions

Prior studies have demonstrated that a baseload wind system based on wind generation and CAES is an economically viable method of generating electricity, particularly when considering carbon emission constraints. A baseload wind system using CAES requires combustion of natural gas fuel and the development of long distance transmission, both of which decrease the environmental and social compatibility of the system. Using biofuels in the CAES turbine reduces the net carbon emissions of the system and increases its renewable character. The use of biofuels may also increase the social acceptability and ease of implementation, as the transmission line, instead of being an unwanted imposition on the character of the land, becomes a method of exporting valuable crops and a source of economic stability. Continued development of CAES and biomass gasification systems will aid the development of large scale, entirely renewable wind/CAES electricity generation systems.

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