

Controllable and affordable utility-scale electricity from intermittent wind resources and compressed air energy storage (CAES)

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Abstract

World wind energy resources are substantial, and in many areas, such as the US and northern Europe, could in theory supply all of the electricity demand. However, the remote or challenging location (i.e. offshore) and especially the intermittent character of the wind resources present formidable barriers to utilization on the scale required by a modern industrial economy. All of these technical challenges can be overcome. Long distance transmission is well understood, while offshore wind technology is being developed rapidly. Intermittent wind power can be transformed to a controllable power source with hybrid wind/compressed air energy storage (CAES) systems. The cost of electricity from such hybrid systems (including transmission) is affordable, and comparable to what users in some modern industrial economies already pay for electricity. This approach to intermittent energy integration has many advantages compared to the current strategy of forcing utilities to cope with supply uncertainty and transmission costs. Above all, it places intermittent wind on an equal technical footing with every other generation technology, including nuclear power, its most important long-term competitor.

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1. Introduction

While renewable energy resources are immense—the US receives more energy from sunlight in 40 min than from all the fossil fuel it burns in 1 yr—the idea that such diffuse, intermittent energy could supply most or all of our power requirements seems far-fetched. In comparison with fossil fuels, with their overwhelming technical advantages such as high energy density, transportability and versatility, as well as their reasonable cost to consumers and enormous profitability for producers, it would appear that solar energy (coupled with much more attention to energy efficiency and conservation [1,2]) could not hope to be a practical source of energy for a modern industrial society.

Yet, as will be shown, the wide disregard of intermittent renewable resources is largely due to our lack of imagina-

tion, not to a lack of viable engineering solutions: their unfavorable characteristics can be dealt with in a cost-effective manner using proven technologies. While renewable resources cannot provide the high levels of return on investment that fossil fuels do—indeed, no new energy source can—they are capable of yielding power on the required scale that is both affordable for consumers and profitable for producers.

If wind-generated electricity is to be a credible alternative to fossil or nuclear power, its technical characteristics must be equal to those of existing suppliers. It must be available as the need arises, independent of the fluctuating source, and in sufficient quantities to power major cities, industrial and commercial complexes, not just isolated homes and farms. Thus challenges of long distance transmission and large-scale energy storage must be acknowledged and addressed.

What is required is that these resources be understood as equivalent to current supplies, not just as fuel savers, and that public policies be crafted to insure that their advantages are recognized in the marketplace.

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While solar thermal power [3] is cost-effective for peaking power in areas with good solar resources, wind turbines now provide the lowest cost renewable electrical energy. Oversized wind turbine arrays combined with compressed air energy storage (CAES) and with high voltage direct or alternating current (HVDC/HVAC) transmission could deliver electricity to demand centers from remote locations that would be both affordable and technically equivalent to that from current power generators [4,5].

An oversized wind turbine array has a maximum output that is much larger than the transmission line capacity, and is coupled to a CAES system with a charge rate about 1.5 times the discharge rate. At low wind velocities, which occur most often, more wind turbines are available to generate power to load the transmission line and reduce the per unit cost of transmission. At higher wind velocities, or if power is not needed, the CAES underground reservoir is filled with compressed air. When the turbine array generates less power than is needed by the load center, compressed air is withdrawn from the reservoir, heated and used to generate electricity, adding to the output of the array. Both short term and seasonal storage [6] of energy is technically possible and economically feasible with wind/CAES systems.

2. Resources

Careful onshore wind resource and wind electric potential assessments exist for the US [7] and Europe, and for offshore Europe [8]. However, for many other areas, even basic onshore wind resource assessments are lacking. In order to be credible, a wind electric assessment must take into account not only the wind resource itself, but also the constraints on deployment of wind turbines. For onshore areas, these include excluding environmentally sensitive regions such as national parks and wildlife refuges, and taking into account population density, current land use and other factors. For offshore resources, such factors as distance from shore, water depth, wave

height, shipping and pipeline routes must also be considered, making offshore evaluations much more involved if they are to be representative.

Estimated onshore and offshore world wind electric potential [9] is compared with projected world electricity demand in Table 1. Based on detailed evaluations for the US and extensive deployment in Denmark, from 1% to 3% of the total land area with good wind resources is assumed to be available for wind turbine deployment, with the lower figure taken for areas with good wind resources but high population density. Even with these constraints, onshore wind electric resources are clearly substantial, and comparable to projected world electricity demand. They are particularly attractive for the industrialized countries in North America and Europe.

These wind electric resources are far from being uniformly distributed. About 50% of the total onshore resources are located in North America and the FSU, and most of this potential is located in remote northern regions. The Great Plains of the USA from North Dakota to North Texas also have excellent resources, but are far from major US cities. However, the offshore resources of the US East coast and the North Sea are of considerable importance as they are not too distant from large cities and industrial areas and are of excellent quality.

Offshore wind resources may be underestimated due to the constraints applied in the evaluation process. For example, the southern section of the North Sea is shallow (water depth less than 40 m) but would require turbine locations greater than 30 km from shore, so these resources are excluded (Table 2). In addition, deployment in water depths greater than 40 m may well be achievable. Significant resources almost certainly exist more than 250 km from major demand centers, especially in Africa; since the first-order potential is not computed for any of the offshore assessments, it is not clear how much the total potential has actually been reduced. Given that offshore wind resources are only beginning to be exploited, the potential for advancing the technology and reducing cost is still large.

Table 1
Projected electricity consumption and wind electric potential (TWh/yr)

Region	Consumption (actual) 2000	Consumption 2025	Estimated <i>onshore</i> wind electric potential ^a	Estimated <i>offshore</i> wind electric potential
North America	4297	6628	14,000	887 ^b
Western Europe	2487	3708	4800	3028 ^c
Latin America	724	1577	5400	1900 ^b
Eastern Europe and former Soviet Union	1504	2642	10,600	235 ^b
Developing Asia	2542	6604	4900	
Africa	388	800	10,600	1200 ^b
Total World	13,629	24,673	53,000	11,300

Sources: Ref. [7] and US DOE Energy Information Administration, Annual energy outlook, DOE/EIA-0383(2003), 2003, Table A2.

De Laquill P and Larson E, US DOE Energy Information Administration, Global Renewable Energy Resource Estimates for the SAGE Model, November 2002.

^a50 m hub height.

^bConstraints: 20 km from coast, 250 km from demand center.

^cConstraints: as for Table 2.

The wind electric potential of the North Sea has been evaluated in greater detail [10] as shown in Table 2. Compared to current or projected consumption in western Europe, the resource is significant, and there is a major effort by the UK, Germany and Denmark to begin to exploit this huge potential. In the UK, there is now an official commitment to supply by 2010, 10% of electricity demand with renewable energy resources, with about 18% of the total 10,000 MW to come from offshore wind turbine arrays [11].

As of June 2005, wind turbine arrays with a capacity of more than 550 MW have been deployed in near-offshore northern Europe, and valuable experience has been gained as to the advantages and disadvantages of these power plants [12]. Installed capital cost for these arrays is about 50% greater than for onshore machines, and stronger offshore winds do not offset this increased cost. There have been significant construction delays due to bad weather and other factors, as one might expect in such a hostile environment. Many of the anticipated project risks, such as turbine and cable failure, have indeed been encountered. Operation and maintenance costs for these offshore projects are not well defined. And while the oil and gas industry has been operating offshore for many years, relevant experience and lessons in technology, law and finance have not yet been applied to offshore wind projects. It must not be assumed that success will come automatically to offshore wind, and there may be some very difficult times ahead for these projects.

Table 2
Maximum offshore wind resources in Europe (TWh/yr)

Water depth (m)	Upto 10 km offshore	Upto 20 km offshore	Up to 30 km offshore
10	551	587	596
20	1121	1402	1523
30	1597	2192	2463
40	1852	2615	3028

Source: Ref. [6].

Constraints: maximum water depth: 40 m; maximum distance to shore: 30 km.

Seabed slope $< 5^\circ$.

Traffic zones, conservation Areas, pipelines and cables with 2 km exclusion corridor, oil platforms with a 10 km diameter buffer, excluded.

Source: Ref. [10].

Table 3
Offshore wind turbine technology

Manufacturer	Vestas	GE-Wind	Enercon	Nordex
Model	V90-3MW	GE Wind 3.6	E-112-45.114	N115
Rated power (MW)	3	3.6	4.5 (6)	5
Rotor diameter (m)	90	104	114	115
Hub height (m)	—	—	124	> 85
Power control	Variable pitch, optispeed	Variable speed, variable pitch, Windvar TM	Direct drive, variable speed, variable pitch	Variable speed, variable pitch

Reference: manufacturers' websites.

Other manufacturers: Pflaider, Repower, Bonus, Gamesa Eolica, NEG-Micon and others.

Wind electric potential assessments are usually based on a turbine hub height of 50 m; as Table 3 shows, this is no longer a limitation for offshore turbines; onshore turbines also can have hub heights of 100 m, with the main constraint being public acceptance. The wind electric potential is approximately 30% greater at 100 m than at 50 m for most onshore sites (open country) and about 15% greater for offshore areas. Wind electric potential estimates should therefore be viewed as indicative, not definitive. There is an immense resource with great potential, but the challenges of transmission and intermittent availability must be overcome if a significant portion of electricity demand is to be supplied from wind.

3. Wind turbine technology

Technology in general has advanced rapidly over the past 30 yr in many areas such as electronics, computers and materials. Wind turbines have benefited in many ways from these advances, and the machines now being built are much more sophisticated and cost-effective than ever before. It should be emphasized that very little government funding has been allocated to wind turbine development; virtually all the advances have been funded by private European companies which now dominate the industry.

For example, wind turbine blades have been made with fiberglass reinforced polyester; replacing glass fibers with carbon fibers [13] has made turbine blades and stronger and lighter. New aerodynamic shapes and new approaches such as pre-bent blades combined with these new materials have been essential for the latest 5 MW machines. These would not have been feasible if blades on 1 MW machines had simply been scaled up.

Variable speed (or an approximation thereto) is now a standard feature on all turbines, reducing component strain and increasing power output. Power electronics allows wind turbine output to be better matched to the utility transmission network, reducing grid voltage fluctuations and unnecessary turbine shut downs. Some turbines feature a generator driven directly by the rotor, eliminating the need for a gearbox. Even tower technology has been refined; the hub height of modern machines can be over 100 m; in the 1990s, the maximum tower height was 50 m.

One example of how all of these advances can be combined is the latest Vestas 3 MW turbine, designed for

offshore applications. By taking advantages of new techniques and materials, the total weight of the new machine is approximately the same as that of an earlier 2 MW model.

A list of the most recent wind turbine designs of several representative manufacturers [14] is given in Table 3. The machines are designed for offshore service, which is the next large market that is beginning to open up.

4. Transmission

It should be emphasized that the limitations dictated by long distance transmission requirements, as distinguished from local transmission requirements for which solutions have been proposed [15], are overwhelmingly political, not technical. Lines can be designed to reduce power losses to acceptable levels (typically a maximum of 1% power loss per 150 km). However, right-of-way for new transmission corridors is exceedingly difficult to obtain, even in rural areas. While landowners in windy areas receive a significant royalty income from wind-generated electricity, such is not the case for landowners over which transmission lines are routed. This issue cannot be ignored: demands on the transmission network are totally different if a significant fraction of (for example) Europe's electricity were to originate over the North Sea, rather than from coal, natural gas or nuclear plants sited much closer to population or industrial centers, as is currently the case.

While existing transmission line technology is adequate, recent advances have lowered costs or expanded the available options.

The 3M Corporation has developed an advanced composite conductor consisting of a core of aluminum wire reinforced with high-strength aluminum oxide fibers surrounded by aluminum alloy wire [16] (conventional wire has a steel core surrounded by aluminum alloy wire). The core has the strength of steel but four times its conductivity and significantly less weight. This wire can carry from 1.5 to 3 times the current (and thus the power) of conventional wire and can be used to replace conventional high voltage conductors in areas with transmission bottlenecks and other critical locations. While it will be significantly more expensive than conventional wire, it will allow upgrading of existing lines. This is probably a reasonable alternative to a long and contentious effort to obtain new right-of-way in populated areas.

HVDC transmission would be essential for transmitting many thousands of megawatts over long distances from remote large-scale arrays of wind turbines. The cost of these lines is known from many existing projects, but is highly dependent on local conditions. For example, Rudervall [17] estimates costs for HVDC lines at \$250/kV km plus \$250 M for converter stations, while for a HydroQuebec 1500 km, 2000 MW HVDC line built in the 1980s, total cost was about \$1,260 M; line costs were \$680/kV km for construction in wilderness regions, and converter stations and filter banks cost about \$320 M [2]. Such

projects are cost effective and routinely used to deliver hydroelectricity to population centers. While wind generated electricity is more expensive than hydropower, for large-scale wind turbine arrays in remote regions, HVDC transmission is a proven technology with known costs, and is a viable technical solution.

A recent development is the so-called HVDC light, which uses insulated gate bipolar transistors and pulsed width modulation instead of thyristors to convert between alternating and direct current. This is suitable for medium to small-scale projects (150 kV, 10–350 MW), and would be essential for offshore arrays where AC transmission losses would be prohibitive. Since this is a relatively new technology, costs are not yet well established [8].

One little-mentioned but significant advantage of HVDC lines is that they can be less visually intrusive than HVAC lines. They need only two conductors and a ground return wire, compared to a double circuit HVAC line with six conductors, and at the same voltage can transmit significantly more power. This could make public acceptance more likely; however, it is no guarantee of such acceptance.

5. Storage

Perhaps the best way (among other possibilities [18,19]) to utilize fully intermittent renewable energy is to make use of large-scale storage systems to insure that power is available as needed. Pumped hydroelectric storage, batteries, superconducting magnets, flywheels, regenerative fuel cells and CAES are candidates for such applications and have been evaluated [20]. With an installed capital cost of about \$890 kW⁻¹ (including 50 h of storage in a solution-mined salt cavern), CAES is the least cost utility scale bulk storage system available. If other factors such as its low environmental impact and high reliability are considered, CAES has an overwhelming advantage.

The immense magnitude of stored energy required to transform the intermittent wind resource to constantly available power supply is not widely appreciated. For example, a 200 MW wind/CAES plant would need a minimum storage capacity of 10,000 MWh, or 50 h of full plant output (this assumes that the wind power density is constant throughout the year). For seasonal storage [6], with the wind power density greater in Winter and Spring than Summer and Fall) a minimum of 40,000 MWh (200 h of full power plant output) would be needed. Clearly, only the most inexpensive of storage media, like air or water, could be used in such an application.

A major advantage of CAES is that the storage volume, of the order of 1 Mm³ for a 200 MW plant, would be located underground in a solution mined cavern or a porous rock stratigraphic or structural trap and would have a minimal environmental impact. In areas without water or suitable reservoir locations, such as the US Great Plains or remote Arctic areas, CAES is the only storage technology option.

CAES [21] was invented in Germany in 1949, and a 290 MW CAES plant has been operating near Huntorf, Germany, since 1978. In the USA, a more modern 110 MW plant with a storage capacity of 2700 MWh has been in operation since 1991 at the Alabama Electric Cooperative in Macintosh, Alabama [22]. CAES is based on gas turbine (or jet engine) technology that has advanced rapidly over the past several decades; modern single cycle combustion turbines now have an efficiency of between 30% and 40%. A turbine is, in principle, a simple machine consisting of a compressor, a combustor and an expander; it extracts energy from a fuel in a thermodynamic Joule cycle. Air is first compressed at constant entropy (isentropic compression) in the compressor, then heated at constant pressure (isobaric heating) in the combustor. Energy is extracted at constant entropy and heat rejected at constant pressure in the expander; the extracted energy is used both to drive a generator to produce electricity and to power the compressor. About 60–70% of the extracted energy powers the compressor, with the remainder used to generate electricity.

CAES can be understood as interrupting the thermodynamic cycle; instead of injecting the compressed gas directly into the combustor, it is stored in an underground reservoir. When electricity is needed, high-pressure gas is withdrawn from the reservoir and the remainder of the cycle completed. Since the system is based on gas turbine technology, it would be highly reliable; other advantages include high rate of power increase and the ability to provide peaking power, spinning reserve and “black start” (starting even if the grid has lost power).

The Iowa Association of Municipal Utilities [23] has proposed building the world's first wind/CAES facility near Fort Dodge, IA. The potential storage volume is about 3.8 Tm^3 located in five highly porous rock formations between 100 and 200 m beneath the surface. This would be sufficient for wind/CAES seasonal storage plants with a total maximum output of about 10,000 MW. The proposed 200 MW CAES plant would utilize only a fraction of the available storage volume and should be operational in 2008.

6. Cost of electricity: what is affordable?

In the US, average wellhead natural gas prices of about $\$2 \text{ mm}^{-1}$ (million) Btu^{-1} in the 1990s [24] and US Geological Survey estimates of reserves to production ratios of more than 70 yr for technically recoverable conventional natural gas [25], with additional resources available from unconventional deposits, made wind generated electricity seem unnecessary and hopelessly uneconomical. In Europe, low cost natural gas was available from the North Sea, North Africa and Russia; only the desire to reduce carbon emissions and to produce as much energy locally as possible enabled wind to gain some market share in a few countries.

A number of factors have transformed the situation. In North America, production of natural gas has reached a plateau, despite a doubling of drilling rig activity, forcing US industries dependent on low cost natural gas to shut down. As of June 2005, US wellhead prices (spot market) were about three times the level of the 1990s, even before the hurricanes that struck the Gulf Coast in August and September of 2005 disrupted oil and gas operations and sent prices above $\$14 \text{ mm}^{-1} \text{ Btu}^{-1}$ (spot market, January 2005) [26] for natural gas. US imports of liquefied natural gas are constrained by lack of supply and increased demand in Europe and the Far East.

In Europe, the production declines in North Sea petroleum and UK sector natural gas have focused attention on Europe's dependence on outside sources of energy. UK natural gas prices have also increased substantially, from about $\$5 \text{ mm}^{-1} \text{ Btu}^{-1}$ [3 p therm^{-1}] in 2005 to over $\$8.75 \text{ mm}^{-1} \text{ Btu}^{-1}$ [5 p therm^{-1}] for 2006 [27]. These rapid price increases have made natural gas a much less economical fuel. For example, natural gas at $\$8.75 \text{ mm}^{-1} \text{ Btu}^{-1}$ in a high efficiency combined cycle plant with a heat rate of 7000 Btu/kW gives a fuel generation cost of $\$0.06 \text{ kWh}^{-1}$ [$\pounds 0.034 \text{ kWh}^{-1}$; $\text{€}0.05 \text{ kWh}^{-1}$]. Capital charges and operation and maintenance increase the cost of gas turbine power to approximately that from a wind turbine, not including transmission and back-up charges (see below).

The rapid industrialization of China and India, which together have a population of 2.3 billion people, has put enormous pressure on many raw material prices, including that of petroleum and natural gas. These countries view imported natural gas as a highly desirable clean fuel, and are already competing with the US, Europe and Japan for liquefied natural gas supplies. With natural gas production reaching a plateau in North America and European demand increasing, it should be expected that these natural gas price increases will be permanent.

Wind turbines currently produce the lowest cost renewable electricity (after hydroelectricity); we will focus on this technology and the policies that have allowed these machines to become the most rapidly expanding source of renewable energy in the world. As of June 2005, the installed wind turbine capacity was 50,000 MW [28] (roughly equivalent to 15 large nuclear power plants), with an annual rate of increase of between 20% and 30%; most of this capacity (75%) is located in Europe.

Wind generated electricity can now be produced and delivered at an affordable cost, i.e. a cost at which it is possible to power a modern industrial establishment, a vibrant commercial sector and provide the population with comfortable living conditions.

This is illustrated by comparing the prices paid by utilities for wind-generated electricity to prices for residential and industrial electricity in Europe (Table 4), which, due to global climate change and energy security concerns, is making a significant effort to move away from fossil fuels for electricity generation. In Europe, utility prices for wind

Table 4
Utility cost (Eurocents, €/kWh) of wind generated electricity in Europe (1996–1997)

Country	Wind electricity price (paid by utility)	Delivered homes (1999) ^a	Delivered industry (1999) ^a
Germany	0.087	0.15	0.06
Italy	0.095–0.046	0.15	0.09
Denmark	0.067–0.080	0.20	0.06
Spain	0.073	0.14	0.05
Netherlands	0.054–0.074	0.13	0.06
Greece	0.057–0.072	0.09	0.05
Portugal	0.54	0.14	0.08
Austria	0.031–0.052	0.16	0.08
Ireland	0.051–0.052	0.11	0.06
England,	0.050	0.12	0.07
Wales			
France	0.044	0.12	n.a.
Sweden	0.030–0.039	0.09	0.03

Source: study by Eugene D. Cross, Leiden University, Int. Institute for Energy Law, Leiden, The Netherlands, for Preussenelektra, Germany, 1997.

^aCost of electricity, IEA, www.iea.org/statist/; 1\$ = 1€.

energy are usually mandated by law and are often set at a fixed percentage of the delivered residential cost. The highest are found in Italy (0.095 €/kWh⁻¹), which has a fairly poor wind regime, and Germany (0.087 €/kWh⁻¹) where one-third of the country has low-grade wind resources, while the lowest are found in Sweden (0.03€/kWh⁻¹), which has abundant hydroelectricity. The comparatively high prices in Denmark and Germany (substantially above production costs in areas with excellent wind resources) have had the desired effect of greatly stimulating wind turbine development and deployment, while Sweden has little installed capacity.

Actual wind electric production costs depend on the site characteristics, wind turbine costs as well as the wind resource. Milborrow [29] assumes a discount rate of 6% (real) and a wind turbine installed capital cost of between €800 and €1150 kW⁻¹ (based on actual project costs in Europe) and computes the cost of electricity to be 0.032 €/kWh⁻¹ for low cost sites with an average wind speed of 9 m/s (wind power density 900 W/m²) and 0.09 €/kWh⁻¹ for high cost sites with average wind speeds of 6 m/s (wind power density about 250 W/m²). He gives a realistic cost spread of 0.04–0.064 €/kWh⁻¹, given that few wind turbines are sited at the best or worst locations.

The cost of electricity for industry is often close to actual production costs from fossil fuel, hydroelectric, and nuclear plants, and ranges from 0.03 €/kWh⁻¹ in Sweden to 0.09 €/kWh⁻¹ in Italy. Current wind energy costs are competitive with these prices, but also do not include costs of standby power or additional transmission capacity. Wind integration costs have been examined by many groups and have always been found to be a small fraction of the cost of wind energy itself when intermittent

electricity is a small fraction of the total demand. For example, a study for the UK National Grid [30] found that if wind supplied 20% of the average UK demand, the additional system cost would be £0.003 kWh⁻¹, or €0.0044 kWh⁻¹.

The cost of electricity for two examples of wind turbine/CAES/transmission plants located in the US Great Plains are given [31] in Table 5; for a wind turbine installed capital cost of \$700 kW⁻¹, which assumes large scale production facilities for the wind turbines, the levelized cost of electricity is \$0.047 and \$0.059 kWh⁻¹ for the two examples considered. While it is difficult to compare these figures to European cost calculations due to exchange rate fluctuations and other factors, it should be clear that even including storage and transmission costs, electricity from these plants will be quite affordable.

Note also that the relatively high prices for electricity in Italy or Austria, a factor of three greater than in Sweden and 50% greater than in Germany, does not mean that the Italian and Austrian economies are in shambles.¹ Energy intensive industries have a clear advantage in Sweden, but Italy does have a modern industrial economy, comparable to northern European countries, and Italian cities and residential standards are comparable to other countries where electricity costs are significantly lower.

It is clear that onshore wind electricity is affordable, even from the point of view of conventional economics, which does not take into account the cost of externalities like pollution and global climate change. Yet since good onshore sites are limited due to high population density in Europe, a key question is whether offshore wind turbines can produce affordable power.

Offshore sites have better wind resources, but foundation, installation, grid connection and other expenses are a factor of 1.4–2.3 times the installed cost of onshore machines, with progressively higher costs for more distant sites (Table 6) [10]; this should be compared to the installed cost of onshore wind turbines of between €800 and €1150 kW⁻¹, as discussed above. These cost comparisons were made assuming 2–2.5 MW wind turbines; as indicated in Table 3, machines of up to 6 MW are now being tested. These cost estimates must be considered indicative, given the rapid progress in wind turbine and transmission technology.

The European Union has mandated a price for offshore wind-generated electricity of 0.091 €/kWh⁻¹ for the first 9 yr and 0.061 €/kWh⁻¹ for the next 11 yr, with an average price of 0.075 €/kWh⁻¹, over the assumed machine lifetime of 20 yr. At this point it is not clear if this will be high enough, even given the rapid improvement in offshore technology, to enable a significant deployment of offshore wind turbines.

¹For comparison, in the US, the average cost of electricity for industrial users was \$0.048 kWh⁻¹ [24]. In spite of this low cost power, manufacturing employment has dropped from 22% of the labor force in 1980 to 14% in 2001. Evidently, low cost electricity alone does not insure a healthy industrial sector.

Table 5
Cost of electricity from a wind/CAES/transmission line power plant

	Ref: Cavallo [4]	Ref: Greenblatt [35]
Turbine cost (\$/kW)	700	700
Wind resource	440 W/m ² at 50 m (7.3 m/s) 33.8% capacity factor	Avg. wind speed 8.2 m/s at 120 m; 35% capacity factor
Base cost of wind electricity \$/kWh	0.033	0.038
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 ⁻¹ (2000 MW, 750 km)
Annual capital charge rate (%)	10.7	11
Levelized cost of electricity	0.047	0.059
Fraction of cost from wind generation (%)	70	65

Table 6
Offshore wind turbines: additional costs as a percentage of wind turbine price

	30	50	70
Distance from shore (km)	30	50	70
Foundations (%)	35.3–38.2	43.5–51.2	38.8–47.5
Installation (%)	8.8–13.3	10.9–18.5	9.7–23.3
Grid connection (%)	31.2–67.2	44.3–82.8	57.2–113.5
Other expenses (%)	7.4–23.9	7.4–23.9	7.4–23.9
Total additional expenses (%)	82.7–142.6	106.1–176.4	113.1–208.2

Assumptions: wind turbine cost, €870/kW; calc. interest, 7.8% (30% equity, 70% debt); availability, 95%; efficiency, 95%; operating costs, 7.5%; inflation, 2%; replacement investment, 35% of WT cost in second decade; service life, 20 yr.

However, even if somewhat higher prices for offshore wind energy are necessary, such electricity will still be affordable and allow for a comfortable lifestyle in economies that move toward a sustainable future, with a much greater emphasis on energy efficiency and conservation.

7. Conclusions

The current integration strategy for wind generators is to rely on fossil fuel and nuclear power for total system reliability [32]. This certainly is reasonable as long as the intermittent generators provide a small or negligible amount of power to the entire system. Exactly how much intermittent power is tolerable, from the point of grid stability, depends on the specific assets of each utility, such as the proportion of baseload, load following and peaking power plants, as well as transmission resources. Denmark, with great effort and good links to the European grid, obtains a yearly average of nearly 20% of its electrical power from wind. Yet this approach, while allowing renewable energy to gain a foothold in the markets has several major disadvantages, both from a practical point of view and from a long-term perspective.

Forcing other generators to provide standby power complicates the task of the utility dispatcher who must assure that power demand is met instantaneously. It compels others to provide services without payment, something that is certain to arouse resentment. In addition, it relegates wind turbines to the marginal role of fuel-

savers, not at all on an equal footing with other power plants.

In the long term, this lack of vision could have significant consequences. The most formidable competitor for renewable energy technologies is nuclear power, which has lowered its cost in the US, and has avoided major accidents everywhere since the Three Mile Island and Chernoble disasters. New plants have been proposed that are smaller, and possibly safer and less costly than current models [33]. While nuclear power plants will never be totally without catastrophic risk, the public may accept this if nothing else seems viable.

One indication of nuclear power's favored status is the number of provisions in the US Energy Policy Act of 2005, signed into law on 8 August 2005, aimed at restarting nuclear plant construction in the US. A production tax credit of \$0.018 kWh⁻¹ (equal to that for wind energy), federal compensation for possible licensing delays for the first two new plants, continued limitation of utility liability for a nuclear accident and establishment of the Next Generation Nuclear Plant program, among other efforts, are included in the bill [34].

It is therefore crucial that it is widely understood that intermittent renewable energy resources can supply a major portion of electricity demand, based on resource availability, economics and technical characteristics. When coupled to compressed air energy storage systems, electricity from these resources is technically equivalent to and economically competitive with that from any nuclear or fossil fuel power plant.

Finally, comparing the projected cost of energy from wind/CAES/transmission plants to current European electricity costs, it is clear that controllable wind energy will be affordable and will be able to provide power to a modern industrial society at reasonable prices.

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