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Wind Power Development: Opportunities and Challenges

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Wind Power Development: Opportunities and Challenges

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Abstract:

In this study, the prospects of wind power at the global level are reviewed. Existing studies indicate that the earth's wind energy supply potential significantly exceeds global energy demand. Yet, only 1% of the global electricity demand is currently derived from wind power despite 40% annual growth in wind generating capacity over the last 25 years. More than 98% of total current wind power capacity is installed in the developed countries plus China and India. Existing studies estimate that wind power could supply 7% to 34% of global electricity needs by 2050. Wind power faces a large number of technical, financial, institutional, market and other barriers. To overcome these, many countries have employed various policy instruments, including capital subsidies, tax incentives, tradable energy certificates, feed-in tariffs, grid access guarantees and mandatory standards. Besides these policies, climate change mitigation initiatives resulting from the Kyoto Protocol (e.g., CO_2-emission reduction targets in developed, the Clean Development Mechanism in developing countries) have played a pivotal role in promoting wind power.

Wind Power Development: Opportunities and Challenges

One of the differences between rich and poor nations is their use of energy. Developed countries became rich because they greatly increased per capita energy use, and the 'green revolution' would never have taken place except for a large increase in energy inputs, especially fertilizers and other chemicals derived from fossil fuels (Smil, 2003). Because of their ubiquity, fossil fuels have become the backbone of industrial economies, while the electricity supply infrastructure is their spinal cord. As developing economies grow, therefore, the use of fossil fuels can be expected to increase significantly over the next decades, as illustrated by the development of China and India. Unfortunately, there are two problems with fossil fuels. First, there are negative spill-over or externality effects from fossil fuel use. Burning of fossil fuels emits gases contributing to global warming and local pollution. Second, and perhaps more important in the longer term, dependence on fossil fuels, particularly oil and gas, raises issues concerning the security of the energy supply. Due to these problems, there is an active debate about whether countries should reduce their dependence on fossil fuels, and switch to renewable energy (RE) sources.

Renewable sources of energy include large-scale hydro, small-scale run-of-river hydro, wind, tidal, solar, wave, municipal solid wastes and biomass for the generation of electricity and space heating, and biofuels (ethanol and biodiesel) for transportation. Some of these sources are severely constrained in a number of ways. For example, in addition to questions about the carbon neutrality of biofuels, increased demand for biofuels reduces cultivated area devoted to food production as land is diverted into energy crops; a consequence has been a precipitous short-run increase in food prices (see Stennes and

McBeath, 2006; Klein and LeRoy, 2007; Searchinger et al., 2008). Burning of forest biomass is perhaps a more promising means for generating electricity (e.g., sawmill residue and 'black liquor' from pulp mills), but currently much of the power that is generated is consumed onsite at sawmills and pulp mills (e.g., Kumar, 2009). Landfill gas generated from solid waste is a potential source of electricity, but even if it is employed on a large scale, its contribution to the globe's electricity needs would be extremely small. The same holds for the incineration of municipal wastes.

Large-scale hydro remains one of the best options for generating electricity, but its main drawbacks relate to inadequate runoff for power generation (especially in regions where water availability is inadequate, intermittent and often unreliable) and negative environmental externalities (changes in the aquatic ecosystem, impediments to fish migration, land inundation by reservoirs, etc.). Environmental opposition will make it very difficult to develop many potential sites for installing a large generating capacity. Similarly, smaller-scale, run-of-river projects will be opposed on environmental grounds and their overall generating capacity will inevitably remain limited in scope, although there might be opportunities to develop run-of-river projects locally (Schuett, 2007).

Tidal and wave energy are also promising. Tidal energy is particularly desirable because of its regularity and predictability. While some tidal barrage systems are in place and experiments are underway with tidal turbines (which function much like wind turbines), huge technological and cost problems still need to be resolved (Blanchfield, 2007). This is even more the case for wave energy conversion systems, which simultaneously suffer from unpredictability and intermittency (St. Germain, 2006).

There are two types of solar energy: (i) solar photovoltaic (PV) converts the sun's energy directly into electricity and (ii) solar heaters heat water (swimming pools, water tanks, etc.). Solar heaters convert up to 60% of the sun's energy into heat, while PV cells convert only 12% to 15% of the energy into electricity, although PV laboratory prototypes are reaching 30% efficiency. One problem with solar electricity is its prohibitive capital costs, which amount to some $13,000 to $15,000 per kilowatt (kW) of installed capacity (IEA, 2005). In addition, solar power is intermittent (e.g., output is greatly reduced on cloudy days), unavailable at night, and, in northern regions, less available in winter when demand is high than in summer. Nonetheless, for remote locations that receive plenty of sunshine and are not connected to an electrical grid, the costs of constructing transmission lines might make solar PV and solar heaters a viable option.

Given the drawbacks of many other renewable sources of energy, wind energy appears to be the renewable alternative choice when it comes to the generation of electricity. As a result, global wind generating capacity has expanded rapidly. However, the euphoria about wind energy needs to be accompanied by a realistic view of its potential contribution to a future energy economy. There is a very active research community looking into the development of wind turbine technology and the integration of wind power into electricity grids, but research in this area is still in its early stages and has yet to answer some basic research questions related to the economics of wind energy. The primary issues relate to the intermittency of wind power output: intermittency raises concerns about backup generating capacity, storage, additional transmission capacity, and potential grid instability. In this study, we review the current status of wind energy, its potential impact on world energy supplies, its prospects for meeting energy needs in developing countries, and some of its limitations from an economic standpoint.

The outline of the paper is as follows: in the next section, we present the status of wind power installation, followed by resource potential and future development prospects. We then discuss wind power generation costs, key barriers to wind power development and policy instruments to overcome those barriers. This is followed by discussions on the intermittency nature of wind energy and grid interconnection issues. The roles of climate change mitigation initiatives to promote wind power are discussed before we draw key conclusions.

1. Current Status of Wind Power Installations

Installed global wind generating capacity expanded rapidly from only 10 megawatts (MW) of installed capacity in 1980 to 94,124 MW by the end of 2007 (Figures 1 & 2, Table 1).[1] At the end of 2007, Europe and North America accounted for 80.5% of global wind power capacity. Overall, developed countries accounted for some 85% of installed wind capacity; after including China and India, this increased to 98.3% of global installed capacity. As indicated in Figure 3, the top ten countries account for more than 86% of total global wind capacity, or 81.1 GW. With the exception of China and India, and a few other countries, very little electricity is produced from wind in developing countries, and especially in the least developed countries, although wind is used on a small scale to drive mechanical devices such as water pumps.

Over the period 1980 to 2007, the growth in wind generating capacity averaged 44.4% per annum, although it slowed to 27.4% since 1999. It is surprising that growth in capacity is forecast to continue at well above 15% until 2012. Installed capacity is expected to surpass 100,000 MW by the end of 2008 (Renewable Energy Industry, 2008). Although wind power registered very high growth rates in recent years, the current role of wind power in meeting

[1] Kilo is abbreviated with k and equals 10^3; Mega (M, 10^6); Giga (G, 10^9); Tera (T, 10^{12}).

global electricity demand is almost negligible as it accounts for only about 1% of the global electricity supply (IEA, 2008).

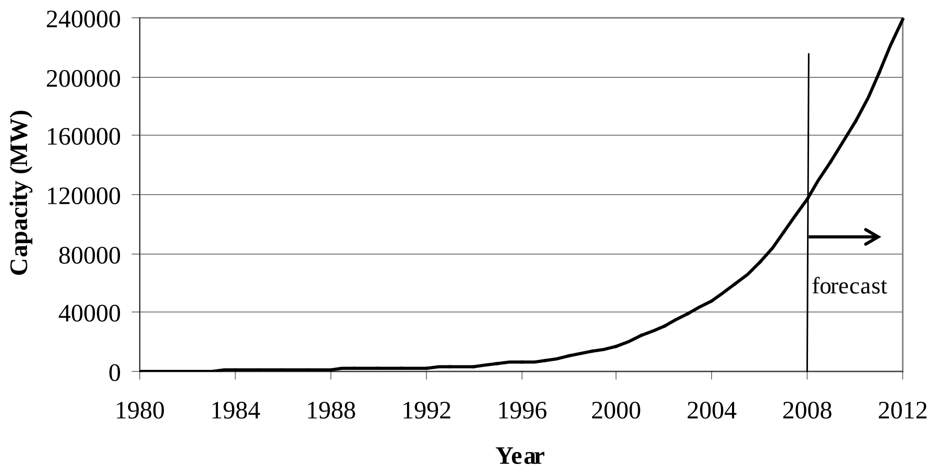


Figure 1: Global wind capacity expanded from 10 MW of installed capacity in 1980 to 94,124 MW by the end of 2007, and is forecast to expand to 240,000 MW by 2012
Source: Renewable Energy Industry (2008)

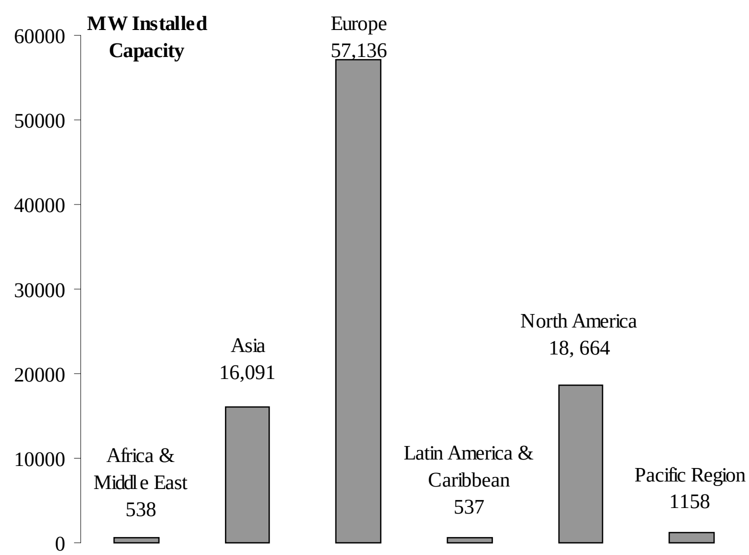


Figure 2: In 2007, the distribution of installed wind capacity indicates that Europe is the leading developer followed by North America and Asia, principally China and India. The top ten countries account for more than 86% of total global capacity (81.1 GW), with developed countries plus India and China accounting for 98.3% (92.4 GW).

Table 1: Cumulative installed wind power capacity (MW), selected countries and

global, 1980-2007

Year	Germany	U.S.	Spain	India	China	Denmark	Other	Global
1980	0	8	0	0	0	5	0	10
1981	0	18	0	0	0	7	0	25
1982	0	84	0	0	0	12	0	90
1983	0	254	0	0	0	20	0	210
1984	0	653	0	0	0	27	0	600
1985	0	945	0	0	0	50	25	1,020
1986	0	1,265	0	0	0	82	0	1,270
1987	5	1,333	0	0	0	115	0	1,450
1988	15	1,231	0	0	0	197	137	1,580
1989	27	1,332	0	0	0	262	109	1,730
1990	62	1,484	0	0	0	343	41	1,930
1991	112	1,709	5	39	0	413	0	2,170
1992	180	1,680	50	39	0	458	103	2,510
1993	335	1,635	60	79	0	487	394	2,990
1994	643	1,663	70	185	0	539	390	3,490
1995	1,130	1,612	140	576	38	637	647	4,780
1996	1,548	1,614	230	820	79	835	974	6,100
1997	2,080	1,611	512	940	170	1,120	1,167	7,600
1998	2,870	1,837	830	1,015	224	1,428	1,996	10,200
1999	4,445	2,490	1,584	1,077	268	1,718	2,018	13,600
2000	6,104	2,578	2,235	1,220	346	2,300	2,617	17,400
2001	8,754	4,275	3,337	1,456	402	2,417	3,259	23,900
2002	11,994	4,685	4,825	1,702	469	2,880	4,545	31,100
2003	14,609	6,372	6,203	2,125	567	3,110	6,445	39,431
2004	16,629	6,725	8,263	3,000	764	3,117	9,122	47,620
2005	18,415	9,149	10,027	4,430	1,260	3,128	12,682	59,091
2006	20,622	11,575	11,623	6,270	2,604	3,136	18,303	74,133
2007	22,247	16,818	15,145	8,000	6,050	3,125	22,737	94,122

Source: Earth Policy Institute (2008).

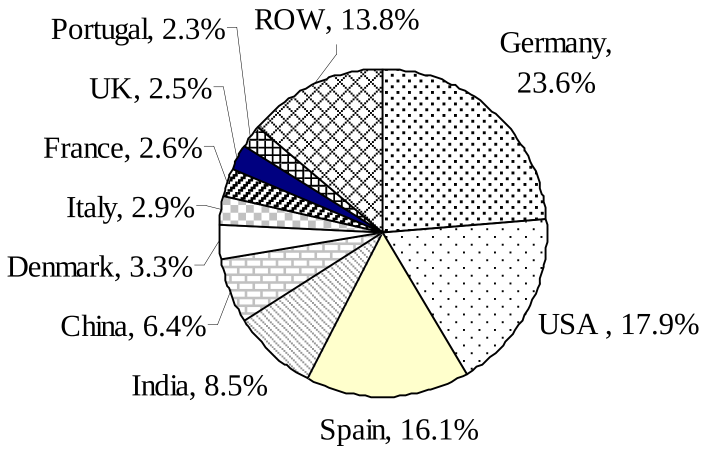


Figure 3: Distribution of global installed wind capacity of 94.1 GW across countries, 2007. Developed countries plus China and India dominate in terms of installed capacity.
Source: Renewable Energy Industry (2008)

2. Resource Potential and Future Development Prospects

It is estimated that the earth has enough wind power resources to meet current global energy needs. Upon analyzing approximately 7,500 surface stations and another 500 balloon-launch stations, Archer and Jacobson (2005) estimate that wind can generate more than enough power to satisfy the world's energy demand. More than 13% of all reporting stations experience annual mean wind speeds greater than the 6.9 meters per second (m/s) at a height of 80 m, which is considered economically feasible to generate electricity. They find that northern Europe (along the North Sea), the southern tip of the South American continent, the island of Tasmania in Australia, the Great Lakes region, and the northeastern and northwestern coasts of North America have the strongest wind power potentials. If turbines were set up in all the regions with wind speeds greater then 6.9 m/s, they would generate 72 TW of electricity, which is almost five times the world's current energy use. However, it is not possible to set up turbines in every region identified due to existing buildings, land rights and other obstacles. Nevertheless, even 20% of those sites could satisfy current world energy consumption. A study initiated by the United Nations' Environment Program (UNEP) to evaluate wind power potential in 19 African countries estimates that the wind power potential could reach 53 TW in those countries alone (InWEnt Consulting, 2004).

As a result of concerns about climate change and higher prices of fossil fuels, wind power has a strong potential for continued rapid deployment. A 2006 joint study by the Global Wind Energy Council (GWEC) and Greenpeace International (2006) estimates that wind energy can make a major contribution to global electricity supply within the next 30 years (see Table 2). The study shows that wind energy could supply 5% of the world's electricity by 2030 and 6.6% by 2050 under the reference wind power scenario. The contribution would range from 15.6% in 2030 to 17.7% by 2050 under the moderate scenario. Wind energy's contribution to world electricity demand would range from 29.1% in 2030 up to 34.2% by 2050 under the advanced scenario. GWEC and Greenpeace International (2006) projections of installed capacity, electricity output and the contribution of wind power to global electricity supply by 2030 and 2050 are provided in Table 2.

Table 2: Projection of wind power development

Scenario	Installed capacity (GW)		Electricity output (TWh)		Contribution of wind power to total electricity generation (%)	
	2030	2050	2030	2050	2030	2050
Reference	364	577	892	1,517	5	6.6
Moderate	1,129	1,557	2,769	4,092	15.6	17.7
Advanced	2,107	3,010	5,176	7,911	29.1	34.3

Note: The reference scenario assumes 15% annual growth rate of wind power until 2010, 10% for 2011-2014 and falling to 3% per annum by 2031. The growth rates under the moderate scenario are: 19% through 2010, 16% for 2011-2014, 15% for 2015-2020 and declines to 10% through 2025 before falling to 5%. Under the advanced wind energy scenario, growth rates are up to 20% to 2015; falling to 17% to 2020; then reduces to 10% for the next five years to 2025, before falling below 5%.
Source: GWEC and Greenpeace International (2006)

Projections of wind power development vary across studies based on the underlying assumptions and projections used in models. In the most recent study, the IEA (2008) estimates wind power development potential under two scenarios referred to as ACT and BLUE. The ACT scenario assumes that extant technologies and ones that are in an advanced state of development can bring global CO_2 emissions back to current levels by 2050. The BLUE scenario assumes that CO_2 emissions can be reduced by 50% from current levels by 2050. While the ACT scenarios are demanding, the BLUE scenarios require urgent implementation of unprecedented and far-reaching new policies in the energy sector.

The global wind power capacity is estimated to increase from 94 GW in 2007 to 1,360 GW in 2050 under the ACT scenario, and to more than 2,010 GW in 2050 under the BLUE scenario. In the ACT scenario, electricity production from wind contributes 2,712 TWh/yr in 2030 and 3,607 TWh/yr in 2050. In the BLUE scenario, wind power adds 2,663 TWh/yr in 2030 and 5,174 TWh/yr in 2050. Wind power constitutes 12% of global electricity production in 2050 in the BLUE scenario compared to 2% at the baseline. Wind power production is expected to grow significantly in OECD countries, and in emerging economies such as China and India. In the BLUE scenario, China leads in wind power generation in 2050 with a 31% share. In both scenarios, onshore generation of wind power dominates, although by 2050 some 20% or more power will be generated by (more expensive) offshore wind farms.

In order to achieve a more diversified energy portfolio, the U.S. Department of Energy recently explored the possibility of supplying 20% of the nation's total electricity demand by wind by 2030. A study commissioned by the Department (USDOE, 2008) concluded that a 20% wind scenario in 2030, while ambitious, could be feasible provided that certain challenges are overcome. First, the U.S. would require 300 GW of wind power capacity by 2030 to meet the 20% wind scenario, which is almost 18 times as high as the 2007 capacity of about 17 GW. Further, it would require construction of more than 20,000 km of high-voltage transmission lines that is opposed by several states as it would likely increase their electricity rates (as such a network would tend to equalize rates across regions).

The USDOE study estimates that upwards of 600 GW of wind generating capacity could be installed at a cost of $60 to $100 per megawatt-hour (MWh), including costs of connecting to the extant transmission system (USDOE, 2008, p.9). The federal government's production tax credit would reduce the cost to investors by about $20/MWh, while hoped-for technological innovations are expected to reduce actual costs as well. Overall, the 20% wind scenario would result in US$43 billion in incremental cost but reduce cumulative CO_2 reductions by more than 7,600 million metric tons by 2030. Thus, by increasing reliance on wind energy for electricity production to 20%, CO_2 emissions can be reduced at a cost of about $5.70 per ton of CO_2 (tCO_2) according the USDOE (2008). If realistic then wind energy development has a promising future in the United States.

One drawback of the forgoing studies that project future wind power generation is their neglect of economic factors. Rates of growth in load and installed wind generation capacity are assumed, as are inherent technological change and cost improvements, but no account is taken of potential demand side policies or prices of alternative energy sources. For example, fossil fuel prices are assumed to continue to rise contrary to recent experience.

3. Costs of Wind Power Generation

A country's ability to rely on wind power for electricity generation and the costs of generating that power depend crucially on the availability of accessible wind locations, existing generating mix, connections to grids in other countries/regions, electricity markets, system operating procedures, the type and size of backup generating capacity (e.g., operating reserve), the extent of hydropower and reservoir storage in the system, costs of buying or renting land, and construction costs. All of these factors are difficult to take into full account a priori. In this section, we consider first the direct costs of building and operating wind turbines, followed by some remarks concerning economies of turbine size. We also identify indirect costs which could be particularly troublesome, although details are provided in section 6.

The IEA (2005) conducted a survey of system operators and power producers in various countries to collect information on the levelized costs of building and operating new generating facilities of all types. Cost data were organized by country and generation technology, and summaries are provided in Table 3. Since data are based on observations from various countries and for various power plant sizes, costs range widely. Solar power is by far the most expensive means of generating electricity, mainly due to high material costs. Both solar and wind generating costs are declining over time as a result of technological advances; thus, these power sources will become increasingly competitive as prices of fossil fuels increase (although they have recently fallen by more than half). However, it is unlikely that, with some notable exceptions, even wind power generation can be competitive with coal in the foreseeable future, even at higher fossil fuel prices. Moreover, offshore wind power is more expensive than onshore wind power due to higher installation costs, greater wear and tear of equipment, higher operating and maintenance (O&M) costs, and high costs of undersea transmission cables.

It is also instructive to look only at construction costs. The term ‘overnight construction cost’ is used to refer to the material, equipment and labor costs of building a power plant without concern about the length of time taken to build the plant – the cost incurred if it is assumed that the power generating facility can be constructed immediately (overnight). It does not attempt to take into account risk associated with the time required to build a nuclear or coal-fired power plant, for example, versus a wind farm or gas plant. Thus, potential cost overruns are ignored, despite the fact they are typical in the construction of nuclear power plants that may take a decade or more to build compared to four years for coal plants and two to three years for base-load gas plants. Further, ‘overnight construction costs’ do not take into account the useful life of generating facilities and such things as the cost of land, although these are taken into account by the levelized investment data provided in Table 3. As a result, data on overnight construction costs are indicative only. Overnight construction costs for various types of power plants are provided in Table 4; costs in the table have been inflated from 2005 values to 2008 dollars using the U.S. CPI (i.e., to account for a 12% rate of inflation). Results indicate that solar, run-of-river hydro and waste incineration have the greatest upfront costs, while gas power plants are the cheapest to build.

Table 3: Weighted averages of levelized lifetime generation costs by plant type, 2005, $US/MWh (2005 dollars)

Plant type	At 5% discount rate					At 10% discount rate				
	Investm't	O&M	Fuel	Total	Range	Investm't	O&M	Fuel	Total	Range
Wind (onshore)	46.00	12.18		58.19	31.10-92.30	71.56	12.20		83.76	46.10-144.20
Wind (offshore)	44.79	22.36		67.13	50.50-94.30	66.80	22.06		88.85	66.00-123.40
Solar thermal	127.40	38.10		165.50	165.50	231.40	38.10		269.40	269.40
Solar PV	157.41	7.52		164.28	120.60-484.80	263.92	7.52		270.78	209.10-1876.40
Small hydro	72.63	19.93		92.55	39.70-142.90	134.83	19.92		154.78	63.50-241.90
Large-scale hydro	44.10	1.60		45.40	45.40	83.40	1.60		84.90	84.90
Nuclear	14.62	8.64	5.16	26.25	20.8-48.00	28.13	8.64	5.29	42.03	31.70-68.60
Coal (lignite)	11.10	5.77	16.77	33.63	29.40-56.90	20.50	5.76	16.34	42.57	37.10-64.40
Coal (high quality)	8.88	5.65	12.69	27.26	17.90-47.80	20.40	5.10	10.49	36.04	25.90-69.10
Coal (IGCC)	13.18	9.79	15.26	38.23	27.30-48.20	24.43	9.79	14.81	48.99	38.20-59.10
Gas (CCGT)	5.93	3.32	37.43	46.68	38.20-60.40	9.48	3.32	36.88	49.67	40.90-62.60
Gas (open)	3.60	1.90	41.20	46.70	46.70	6.40	1.90	40.80	49.00	49.00
CHP gas (CCGT)	9.88	9.84	47.45	47.11	28.30-62.30	15.79	9.84	46.56	52.22	31.90-80.90
CHP gas (coal)	13.57	11.35	22.39	33.41	25.00-36.80	24.12	11.33	21.63	43.11	34.80-46.90
CHP (other)	7.48	3.95	43.92	34.20	29.40-96.30	11.75	4.02	43.41	38.17	33.50-99.50
Waste incineration	63.33	18.21	-71.80	9.73	-4.00-24.30	97.07	18.21	-71.80	43.47	20.60-52.30
Biomass	15.09	9.95	16.62	41.65	37.30-85.20	28.30	9.95	16.53	54.86	50.30-100.50

Source: Authors' calculations using data from IEA (2005). Costs for each type of plant are weighted by generating capacities of individual plants in that category for which cost information is available.

Table 4: Overnight construction costs for power generators, 2005, $US per kW of installed capacity (2008 dollars)

Type	Weighted Average[a]	Minimum	Maximum
Wind onshore	$1,457	$1,093	$1,830
Wind offshore	2,174	1,833	2,937
Solar thermal	3,108	3,108	3,108
Solar PV	4,713	3,767	11,384
Run of river/small hydro	5,623	1,794	7,823
Large-scale hydro	1,726	1,726	1,726
Nuclear	1,837	1,203	2,811
Coal (lignite)	1,468	1,313	1,665
Coal (high quality)	1,388	805	2,629
Coal (IGCC)	1,740	1,530	2,168
Gas (CCGT)	651	408	1,154
Gas (open)	514	514	154
CHP (CCGT)	961	627	1,756
CHP (coal)	1,503	1,409	1,737
CHP (other)	1,002	821	2,869
Waste incineration	5,579	1,653	7,855
Combustible renewables	1,953	1,904	2,439

Notes:
[a] Authors' calculations based on plants in different countries and weighted by plant capacity.
Source: IEA (2005)

A recent study prepared for the World Bank by URS (2008) specifically examined the costs of building new power plants. It employed original equipment manufacturer data for the United States, India and Romania to provide estimates of the costs of constructing generating plants. Results are provided in Table 5. The data provided for the World Bank can be compared with the IEA (2005) information provided in Table 4. The comparison suggests that real construction costs have increased between 2005 and 2008. However, the URS (2008) uses material prices prior to the global financial crisis – when material and fuel prices peaked – rather than the more modest prices observed recently (late 2008).

Table 5: Overnight construction costs for power generators in the United States, India and Romania, 2008, $US per kW of installed capacity (2008 dollars)

Generation Plant	U.S.	India	Romania
Simple cycle plant, 5 MW	1,380	1,190	1,240
Gas turbine simple cycle plant, 25 MW	970	830	870
Gas turbine simple cycle plant, 150 MW	530	440	480
Gas turbine combined cycle plant, 140 MW	1,410	1,170	1,140
Gas turbine simple cycle plant, 580 MW	860	720	710
Coal-fired steam plant (sub), 300 MW net	2,730	1,690	2,920
Coal-fired steam plant (sub), 500 MW net	2,290	1,440	2,530
Coal-fired steam plant (super), 800 MW net	1,960	1,290	2,250
Oil-fired steam plant (sub), 300 MW net	1,540	1,180	1,420
Gas-fired steam plant (sub), 300 MW net	1,360	1,040	1,110
Diesel engine-generator, 1 MW	540	470	490
Diesel engine-generator, 5 MW	630	590	600
Wind farm, 1 MW x 100 = 100 MW (onshore)	1,630	1,760	1,660
Photovoltaic array, ground mounted, $/kW (AC)	8,930	7,840	8,200

Source: URS (2008)

The economic viability of commercial-scale wind installations depends on several direct and indirect factors. Direct factors relate to the technical specifications and size of the wind turbines. If one builds a wind turbine with an 80 m rotor blade diameter and a generator of 75 kW, say, then it would run with a capacity factor (=actual power generation / [rated capacity × 365 days × 24 hours]) of around 75% in almost any wind climate, but its cost might be some 90-95% of that of a 2 MW turbine as one would largely save only on the generator and gearbox components. Despite the high capacity factor, annual energy production would be only 657 MWh, while it would be 5,256 MWh for a 2 MW turbine assuming a capacity factor of 30%. It pays to build a larger turbine in this case, but not always.

Clearly, there are economies of scale in turbine size as costs per MWh decline with larger turbines, even though the capacity factor might also fall. However, the name-plate capacity and thereby the size of turbines cannot be increased indefinitely, as the generator and gearbox become more difficult to turn at the low wind speeds common in many regions. Technical improvements seek, among other things, to improve power output of large turbines at lower wind speeds, thereby increasing the capacity factor and reducing costs – in economic terms, technical improvements seek to shift the long-run average cost curve downwards and to the right. Whenever a country or company decides to install one or more wind turbines, the capacity of the turbine is chosen to optimize both the wind environment and the economic environment in which turbines function. Thus, wind turbines of different capacities might be installed in different countries even if the wind profiles are the same. Nonetheless, there exists a mainstream market segment where there is substantial competition between component suppliers: twenty years ago the capacity of mainstream turbines averaged around 100 kW, 10 years ago around 600 kW, and today between 1.5 and 2 MW.

In the United States, the vast majority of turbines in place as of 2006 had a capacity of 1.5 MW, with only eight turbines with a capacity of 3 MW; in Germany, average turbine capacity was 1.14 MW in 2007, but 're-powering' subsidies are in place to encourage replacement of old turbines with new ones (GWEC, 2007).

Globally, the vast majority of turbines currently in operation do not exceed 2.5 MW in capacity. In developing countries, wind turbines are in general smaller, as they are located in rural areas away from large electricity grids. One reason is logistics: Large cranes for the erection and major overhaul of large-sized turbines are not available at reasonable cost, while road, bridge and tunnel infrastructure are incapable of moving rotor blades of 40 m length or more. In France, for example, the average size of newly installed turbines increased from 1.2 MW in 2005 to 1.7 MW in 2007, and is expected to be 2.0 MW in 2008, but these turbine sizes could not be erected in developing countries for the reasons mentioned.

Interestingly, the highest average capacity factors among OECD countries are found in Australia (35%), Canada (30%) and the United States (31%); only for the United Kingdom (27%) and Ireland (25%) are average capacities at or above one-quarter (GWEC 2007). Despite this, when calculating the benefits of wind, some UK studies assume that capacity factors of 35% are typical (e.g., Gross et al., 2006, 2007). Capacity factors vary from one site to another. Economic reasoning suggests that lower-cost sites are chosen before higher cost ones so that, ceteris paribus, sites with the highest capacity factors are chosen first; thus, as new wind facilities are installed, they will tend to have lower capacity factors. This could explain why Australia, Canada and the U.S. have the highest capacity factors among OECD countries – these countries have the most open spaces suitable for wind farm development and still have to expand wind investments onto less desirable sites.

Indirect costs of wind power generation, on the other hand, include the costs of balancing load across extant generators as a result of wind variability and the costs of reserve capacity associated with the probability that wind is unavailable at certain times (see Lund, 2005; Prescott et al., 2007; Benitez et al., 2008; Maddaloni et al., 2008a, 2008b). These are discussed in more detail below.) It also depends on the externality costs that turbines impose on each other when they are located in close proximity, such as in wind farms. Turbines create air turbulence that affects output from downstream turbines. These indirect costs are not discussed here (see Rooijmans, 2004 for more detail).

4. Barriers to Wind Power Development

Despite the apparent advantages of wind power for development, wind power faces major barriers, particularly in developing countries. These can be classified into technical barriers, economic or financial barriers, market barriers, institutional or capacity barriers, and others.

Perhaps the most critical technical barriers are lack of access to transmission lines, difficulty of getting cranes and/or turbine components to sites (as mentioned in the preceding section), and the challenges related to the intermittent nature of wind (Liik et al., 2003; Lund, 2005) that are discussed in more detail below. Another important technical barrier, particularly in developing countries, is the lack of data (e.g., detailed wind mapping or wind Atlas) needed to forecast wind profiles. This leads to high uncertainties regarding wind power outputs, thereby discouraging investors from developing wind power. Equipment misspecification or lack of harmonizing in local systems also poses constraints. For example, at the early stage of wind power development in the Indian State of Gujrat, second-hand equipments purchased from California could not operate effectively within the Western Electricity Grid of India, which typically undergoes large fluctuations in frequency and where outages are common-place (Amin, 1999).

The financial barriers include high upfront capital costs and uncertainty regarding financial returns (e.g., resulting from lower than anticipated capacity factors). These limit access to financing. The capital costs of wind power continue to be an obstacle to its adoption, with average costs rising as sites with lower inherent capacity factors (less attractive wind profiles) are relied upon to expand wind power output. The costs of constructing transmission lines from a wind farm to an electricity grid can be onerous ($50,000 to $550,000 per km or more). This makes wind generation less financial attractive relative to thermal power plants that can be constructed near existing transmission corridors at lower costs per kW of installed capacity (Tables 4 and 5).

The economic feasibility of wind power remains paramount to the eventual success of a wind industry. Even in rich countries, when it comes to off-grid electrification, companies may be hesitant to make investments because the long-term costs of small, wind-driven grids are difficult to predict and rural communities may lack financial resources to make payments; thus, the off-grid electricity market is somewhat risky (Reiche, Covarrubias and Martinot, 2000). This may be more the case in developing countries where there is also a greater need for off-grid electrification. Thus, wind power developers face difficulties in raising local equity due to the high level of technical and financial uncertainties (e.g., unfamiliar and potentially risky investment with uncertain returns). For the same reasons, wind power developers also face difficulties in securing loans. Loan requests are often declined or face high interest rates due to high risk premiums. Because of these financial barriers, wind power may not be an attractive portfolio for private investors, particularly in developing countries.

Unless implemented under the CDM or JI, wind power does not receive 'green' benefits, while fossil fuels are not taxed for their environmental externalities. This results in an uneven playing field for wind power as it has to compete with large fossil fuel technologies that are also cheaper and have the opportunity to benefit from economies of scale. This can be a substantial market barrier to wind power. Furthermore, wind farms are generally smaller in terms of installed generating capacity, while wind power developers have fewer resources than companies with large thermal power plants. This impedes the ability to borrow capital on similarly favorable terms. In addition, small wind projects face higher transaction costs at every stage of project development cycle.

Lack of proper institutions and local capacity are additional key barriers to wind power development, specifically in developing countries. In many countries, production and distribution of electricity are still controlled by a monopolist, often the state. There is a general lack of economic institutions for facilitating contracts (power purchase agreements) between the wind power developers and system operators (Beck and Martinot, 2004). Further, many wind power projects are implemented as turn-key projects with bilateral or multilateral funding from rich countries. Once the projects are handed over to a local company or system operator, they encounter constraints related to a lack of operating skills and equipment parts. This eventually results in inefficiencies, outages and even shutdown of wind farm facilities. Since it is mainly small-scale, remotely located wind power facilities that suffer from these types of barriers, this could eventually lead to a loss of future interest in small-scale wind power development in remote villages (UNEP, 2001).

Besides the aforementioned barriers, wind power also suffers from other barriers. In some countries, wind power must meet stringent licensing requirements. Wind turbines along migratory bird paths and/or in coastal areas often need to address specific environmental concerns before they can be erected. Competition for land use with agricultural, recreational, scenic or development interests can also occur (Beck and Martinot, 2004).

5. Policy Instruments to Support Wind Energy

Considering these barriers, many countries have developed strategies to reduce or overcome them. They have also set renewable energy targets. As of 2005, 43 countries had renewable energy targets, of which ten were developing countries: Brazil, China, the Dominican Republic, Egypt, India, Malaysia, Mali, the Philippines, South Africa and Thailand (Martinot, 2005). Various incentives are in place to promote wind energy, including development subsidies, tax breaks and feed-in tariffs. In the United States, for example, a wind energy production tax credit (PTC) is used to encourage investment in wind generating capacity. The PTC provides an income tax credit of 2.0¢ per kWh for production of electricity from wind and other renewable sources. It is adjusted annually for inflation, is in effect for the first ten years of production, but applies only to large-scale power producers and not the installation of small turbines for individual use (see Steve, Severn and Raum 2008). India also promotes growth in its wind industry by supplying generous tax credits to the private sector (Martinot, 2002). Other countries provide feed-in tariffs or tax incentives amounting to 1.5¢ (in U.S. funds) to 10¢ or more per kWh delivered to the grid; the length of time a project can collect such payments varies, and downward sliding payment scale is common.

Other forms of support for wind development, and even direct investment by the state, can be found. As of 2005, 25 developed and nine developing countries provided feed-in tariffs for wind energy, the same number of developed and six developing countries had provisions to provide capital subsidies, and 26 rich and nine poorer nations provided other forms of aid (reduced taxes, tax credits, etc.) (Martinot, 2005). Further, 15 countries provided tradable (renewable) energy certificates that could be used, for example, on the European climate exchange (Japan and Australia were the only non-European countries to offer this option). Jurisdictions that do not offer subsidies also tend to have little or no installed capacity to generate electricity from wind (AWEA, 2002).

In Table 6, we provide a summary of policies in 63 countries for which we could find information regarding their wind potential, renewable energy targets and actual policies for increasing reliance on wind energy. Most countries have relatively good to excellent potential to generate wind power, especially if offshore potential is taken into account in the case of coastal countries. It is also clear that state ownership and public investment are often required to facilitate the development of wind power.

Table 6: Wind potential, policies and opportunities in selected countries, 2007

Country	Wind potential[a]	Renewable energy target[b]	Wind energy policy
Albania	NE mountains, south hills have potential	400 Gwh/year (4% of generation from wind) by 2020	No information is available
Argentina	Immense	300 MW by 2010	US$10/MWh subsidy for first wind farms (no time limit noted); tax credits
Australia	Good	2% of electricity from renewables by 2010, 20% (9.5 TWh) by 2020; 10 GW additional wind by 2020 (0.8 GW installed in 2007)	Mandatory targets, construction of new transmission lines to facilitate wind (including connection to hydroelectric facilities; tradable energy certificates
Austria	No information	78.1% of electricity output from renewables by 2010, 10% from new renewable sources by 2010	Feed-in tariffs for 12 years, declining from full tariff after 10 years. Rate varies from year to year. Also, subsidies of €5.1 million over three years for new wind farms; tradable energy certificates
Brazil	143.5 GW	≥ 928 MW additional wind by 2010, additional 3,300 MW from wind, small hydro, biomass by 2016	Feed-in tariffs; some public investment
Belgium	No information	6% of electricity output from renewables by 2010	capital subsidies, tax incentives, tradable energy certificates
Canada	Abundant	2.8 GW of installed wind by 2010; 12 GW by 2016 (4% of electricity demand)	1¢/kWh premium for 10 years, plus construction subsidies and provincial incentives (e.g., 11¢/kWh for renewable projects in Ontario)
Chile	Significant	15% of added power capacity from renewables during 2006-2010; 257 projects considered	No payment of dispatching costs to system operator; exemption from transmission cost; $150,000 subsidy per project
China	1,000 GW onshore; 300 GW offshore	10% of primary energy consumption from renewables by 2010, 15% by 2020; installed wind capacity to increase from 6 GW in 2007 to 30 GW by 2020 (5 GW to be added in 2008 alone)	Combination of regulation and concessions; feed-in tariffs, capital subsidies, tax incentives; International subsidies under Kyoto's CDM, 16.6 GW in CDM pipeline; CDM payment €9-11/tCO_2. 100 MW projects, no turbines under 600 kW capacity
Costa Rica	Excellent; some of globe's highest winds	49.5 MW to be installed under contracts by 2026	State ownership; some feed-in tariffs
Croatia	No information	400 MW from renewables	No information is available
Cyprus	No information	6% of electricity output from renewables by 2010	feed-in tariffs and capital subsidies for wind production
Czech Republic	No information	5-6 % of TPES by 2010, 8-10% of TPES by 2020, 8% of electricity output from renewables by 2010	Feed-in tariffs for all renewables; capital subsidies, tax incentives and tradable energy certificates
Denmark	Significant	29% of electricity output from renewables by 2010	June 2004 legislation; feed-in tariffs, market premium of 0.10 DKK (€0.0134) per kWh, tax incentives, tradable energy

	certificates replaced by premium

Table 6. Continued

Dominican Republic	No information	500 MW from renewables by 2015	No information is available
Egypt	20 GW	3% of electricity from renewables by 2010, 20% by 2020; 12% (7.2 MW installed capacity) from wind	Priority grid access; long-term contracts; price concessions
Estonia	No information	5.1% of electricity output from renewables by 2010	Feed-in tariffs and some tax incentives
European Union	Abundant	12% of total energy to come from renewables by 2010; 20% by 2020; share in electricity to reach 21% by 2010	Incentives vary among EU-27 countries, but include concessions for wind, tax incentives, subsidies, voluntary agreements, environmental taxes, tradable energy certificates
Finland	300 MW onshore; 10,000 MW offshore	31.5% of electricity from renewables by 2010; 300 MW of installed wind capacity by 2010	Capital subsidies, tax incentives and tradable energy certificates
France	Abundant	21% of gross electricity by 2010; generation target of 25 GW (incl. 6 GW offshore) by 2020, with 4 GW offshore by 2015	Feed-in tariff of 8.2¢€/kWh for 10 years; capital subsidies, tax incentives, tradable energy certificates, public investment
Germany	45 GW onshore; 10 GW offshore	Already exceeds EU target for 2010 (12.5% of electricity from renewables by 2010); 25-35% of energy from renewables by 2020	Feed-in tariffs of 8.19¢€/kWh for 5 years ('initial') plus 5.17¢€/kWh for 20 years (basic); vary according to quality of wind development. Preferential zoning. Subsidies for replacing old turbines with new and offshore construction. Offshore transmission connection to be paid by system operator (consumer).
Greece	Substantial	20.1% of electricity from renewables by 2010; 3,372 MW wind by 2010; already Crete grid >10% wind	Feed-in tariffs for wind (amount not known), R&D subsidies, capital subsidies, tax credits
India	65 GW	Annual wind capacity additions of 2 GW over coming years	No national feed-in tariffs or quota; only tax incentives. States use fee-in tariffs; 10 of 29 states require utilities to source 10% of power from renewable sources. Public investment, capital subsidies. Subsidies via CDM for 4.0 GW as of 2008.
Hungary	Unknown	Must meet EU targets, 3.6% of electricity output from renewables by 2010, but National grid has limitations: 300 MW in 2010, 800 MW 2015	Feed-in tariff of 23.8 Ft/kWh (€0.0985/kWh); costs are high; require subsidies from the EU; tradable energy certificates
Iran	6.5 GW minimum, perhaps 30 GW	500 MW installed wind capacity by 2010 (19 MW in 2007)	Price guarantees for wind below payments for fossil fuel generated power; to be changed.
Ireland	179 GW	13.2% of electricity from renewables by 2010; 1.1 GW of installed wind capacity by 2010 (520 MW offshore)	Fixed feed-in tariff for 15 years
Israel	No information	5% of electricity from renewables by 2016	Feed-in tariffs started in 2004

Table 6. Continued

Italy	7,000 MW onshore	25% of electricity from renewables by 2010 (hydro, geothermal already contribute but are saturated; rely on biomass and wind); 8 GW wind capacity by 2010 (2.7 GW in 2007); 12 GW by 2020	Feed-in tariff for wind replaced by quota and Green certificates; feed-in tariff for solar remains.
Japan	Significant offshore and along coast, but subject to typhoons	7% of total primary energy supply from renewables by 2010; 1.35% of generation capacity to come from wind by 2010; wind target of 3 GW installed by 2010	Weak incentives and some obstacles to wind power development
Jordan	No information	15% of energy from renewables by 2020	No information is available
Korea	No information is available	5% of energy from renewable sources by 2011, 10% by 2020; wind target of 2.25 GW installed by 2012	Public opposition to wind; no subsidies in place; eligible for CDM subsidies
Latvia	Favorable	6% of TPES (excluding large hydro) by 2010, 49.3% of electricity output from renewables by 2010; 500 MW of installed wind capacity, focus on offshore as winds average 5.7m/s	State funding to support of R&D
Lithuania	No information	12% of TPES by 2010, 7% of electricity output from renewables by 2010; 200 MW wind capacity by 2010	€ 0.0637/kWh feed-in tariff (no time limit given)
Luxembourg	No information	5.7% of electricity output from renewables by 2010	feed-in tariffs and some capital subsidies and tax incentives
Mali	No information	15% of electricity from renewables by 2020	Small subsidies for rural solar energy, but not wind energy
Malta	No information	5% of electricity output from renewables by 2010	some tax benefits to wind producers
Mexico	Tremendous potential: 21+ GW	Excluding large hydro, renewable generation to supply 8% of energy by 2012; 404 MW of installed wind capacity by 2017	Long-term power purchase agreements; investments depreciated in one year
Morocco	Vast potential due to high wind speeds along coast (est. cap. factor >40%)	10% of energy and 20% of electricity consumption from renewables by 2012; 1 GW installed capacity by 2012	Preferential treatment of wind access to grid
Netherlands	6,000 MW offshore, 1,500 MW onshore	5% of energy from renewables by 2010, 10% by 2020; 9% of electricity output by 2010; 20% of domestic energy demand supplied by wind by 2020, 10% of primary energy from renewables by 2020	Involved in offshore consortium with Germany and UK to integrate 2000 turbines into grids of these countries. No information on subsidies available.
New Zealand	Excellent	90% of electricity from renewable sources by 2025 (65% currently, mostly hydro, 1.5% wind), 30 PJ of new renewable capacity (including heat and transport fuels) by 2012	Emissions trading scheme to include electricity sector in 2010 favors renewables; some environmental opposition to wind.
Nigeria	No information	7% of power generation from renewables by 2025	No information is available

Table 6. Continued

Norway	High	State-owned company seeks to install 1 GW wind capacity and produce 3 TWh by 2010; no other targets as Norway highly reliant on hydropower	Feed-in tariff of 8 øre /kWh (approx. €10/MWh) for 15 years; for each øre above 45 øre/kWh, tariffs declines by 0.6 øre (1 NOK = 100 øre); capital subsidies; tradable energy certificates
Pakistan	No information	5% of power generation from renewables by 2030, 1,100 MW of wind power	Limited feed-in tariff at 9.5¢ per kWh
Peru	No information	6,200 kW of installed wind capacity by 2014	No information is available.
Philippines	No information	4.7 GW installed capacity of renewables by 2013	Some tax credits and incentives; public investment
Poland	13.5 GW onshore; possible 2.0 GW offshore, but limited by protected areas	7.5% of total primary energy supply (TPES) from renewables by 2010; 15% by 2020; 7.5% of electricity from renewables by 2010. Estimate: 2.5 GW by 2010, 5 GW by 2015, 12 GW by 2020	Power purchase obligation requires utilities to obtain 7.5% from renewables by 2010. Capital subsidies, tax incentives and public investment
Portugal	700 GWh/year	3,750 MW of electricity generation from wind by 2010, 5,100 MW by 2013, 45.6% of electricity output from renewables by 2010	More competition to promote wind by linking the grids of Portugal and Spain; feed-in tariffs, capital subsidies, tradable energy certificates
Russia	30,000 TWh/year (37% in Europe, 63% in Siberia/Far East)	No targets	No information is available.
Singapore	No information	Installation of 50,000 m^2 of solar thermal systems by 2012; complete recovery of energy from municipal waste	No information is available.
Slovakia	No information	31% of electricity output from renewables by 2010	Feed-in tariffs and tax credits; public investment
Slovenia	No information	33.6% of electricity output from renewables by 2010	Feed-in tariffs; no capital subsidies or tax incentives for wind
Spain	40 MW onshore; 5 MW offshore	30.3% of electricity consumption from renewables and 29.4% from wind, with 20 GW installed capacity, by 2010	Wind producers choose: fixed tariff of 7.32¢€/kWh reduced to 6.12¢€/kWh after 20 years, or premium of 2.93¢€/kWh combined with cap (8.49¢€/kWh) and floor (7.13¢€/kWh) prices; tax credits and public investment are also used
South Africa	32,228 MWh (5,000 MWh national grid, 111 MWh rural min-grid, 1,117 MWh off-grid, 26,000 borehill windmills)	10,000 GWh or 0.8 Mtoe renewable energy contribution to the final energy consumption by 2013	No information is available.
Sri Lanka	No information	No target; potential is being examined.	USAID funded wind mapping survey; feed-in tariffs
Sweden	No information	60% of electricity output from renewables by 2010, 10 TWh of electricity production from wind power by 2015 (4 TWh onshore, 6 TWh offshore)	Feed-in tariffs, tax incentives, capital subsidies, tradable energy certificates; production support or environmental bonus that declines each year; easier certification of designated sites

Table 6. Continued

Switzerland	4,000 GWh	3.5 TWh from electricity and heat by 2010	feed-in tariffs; no capital subsidies or tax incentives for wind
Taiwan	1 GW onshore; 2 GW offshore	328.96 MW in 3-phase wind power project by 2011	R&D is subsidized
Thailand	No information	8% of total primary energy from renewables by 2011 (excluding traditional rural biomass)	Feed-in tariffs (but only for small power producers) began in 2000; capital subsidies
Tunisia	1 GW	No target; 120 MW of installed capacity due by 2009	No information is available.
Turkey	88 GW	Projected shortfall in conventional generation. 2% of electricity from wind by 2010	Feed-in tariffs of 5.0-5.5¢€/kWh for 7 years; capital subsidies. Guaranteed connection to national grid. Improved links with EU grids to stabilize power system.
Ukraine	30 TWh/year (16-35 GW capacity)	Targets set for 2050. Prediction: 11 GW of wind power by 2030, wind generation to reach 42 TWh by 2050	No information is available.
United Kingdom	30 GW offshore; onshore not provided	10% of electricity from renewables by 2010; 15% of all energy by 2020 (13 GW onshore, 20 GW offshore wind capacity to meet 15% target)	Renewable Obligation Certificate provides premium to bulk electricity generated by large-scale operators; capital subsidies, tax incentives, tradable energy certificates
United States	Huge potential, >3,000 GW	Target under consideration: supply 20% of energy by 2030	Federal production tax credit of $0.02/kWh (adjusted for inflation) for wind generated power for 10 years. Some states aid in transmission planning.
Uruguay	No information	20 MW of electricity generation to come from wind power, with 10 MW from independent producers	Government decree in 2006 encourages development of wind power

Notes:
[a] Wind potential is frequently described by terms such as ‘excellent’, ‘significant’, ‘abundant’, ‘immense’, ‘huge’, ‘favorable’ or ‘good’. No attempt is made to define these terms as they are the terms used in the publications to indicate wind potential. Clearly, the terminology suggests enthusiasm for the future of wind power development and that is how they should be interpreted. In other cases, actual capacity or production estimates are provided, while in some no information could be found in the original source.
[b] TPES stands for total primary energy supply

Sources: Martinot (2005), Martinot (2006), IEA (2006a, b), World Energy Council (2007), OECD and IEA (2008, as viewed May 26, 2008).

6. Integration of Wind Power into Electricity Grids and the Costs of Mitigating Climate Change

Intermittency is the greatest obstacle to the seamless integration of wind generated power into electrical grids. When there is no wind, no power is generated; the wind comes and goes, and does not always blow with the same intensity. According to Scott (2007), wind is a whimsical source of power. Wind power enters an electrical grid whenever there is adequate wind, it is non-dispatchable. Because of this intermittency, the supply of wind power will fluctuate more than that of traditional generating sources. The indirect costs associated with intermittency are (1) the costs of additional system reserves to cover intermittency, and (2) the extra costs associated with balancing or managing an electricity system when power from one (or more) generation sources fluctuates.

Consider first the issue of reserves. By installing wind generating capacity, greater system balancing reserves are required than would normally be the case if an equivalent amount of thermal or hydro capacity were installed, even after adjusting for the lower capacity factors associated with wind (Gross, Leach and Bauen, 2003; Kennedy, 2005; Gross et al., 2006). The reliability of power from wind farms due to a high variability in wind is lower than that of thermal or hydro sources of power and must be compensated for by greater system reserves.

Suppose that σ_s and σ_d are the standard deviations of supply and demand fluctuations, respectively. Then, as a rule of thumb, a system operator requires reserves equal to three standard deviations of all potential fluctuations, or reserves = $\pm 3\sqrt{\sigma_s^2 + \sigma_d^2}$ (see Gross et al., 2006, 2007; DeCarolis and Keith, 2005). If wind farms are added to an existing grid, required reserves must be increased to $\pm 3\sqrt{\sigma_s^2 + \sigma_d^2 + \sigma_w^2}$, where σ_w is the standard deviation associated with wind intermittency. If $\sigma_w > \sigma_s$ and wind replaces other generation that is more reliable, then reserves must increase; if $\sigma_w < \sigma_s$, reserve capacity would decline. How large must the additional reserves be? According to Gross et al. (2006, 2007), assuming no correlation between demand and variable supply from wind, additional reserve requirements would be small. The standard deviations of wind fluctuations amount to 1.4% of installed wind capacity for a 30-minute time horizon (regulating or fast-response reserve) and 9.3% of installed capacity over a four-hour time period (contingency or standing reserve). Assume 10 GW of installed wind capacity, σ_w = 140 MW for regulating and σ_w = 930 MW for contingency reserves, and total generating capacity of 24.3 GW. Then, if $\sigma_s+\sigma_d$ = 340 MW, regulating reserves would need to equal 1020 MW (= $3 \times \sqrt{340^2}$) without wind and 1181 MW (=$3\times\sqrt{340^2+140^2}$) with wind, while respective contingency reserves would need to be 6780 MW and 7332 MW. Thus, wind intermittency requires increases in regulating reserves of 15.8% (161 MW) and contingency reserves of 8.1% (552 MW).[2]

In addition to the need for greater system reserves, there is a second cost associated with the need to retain system balance, the added cost of managing the grid (Lund, 2005). How the grid is to be managed depends on the policy implemented by the authority. If the grid operator is required to take any wind power that is offered, wind power is then 'must run' (non-dispatchable). In that case, extant generators may need to operate at partial capacity, although they must be ready to dispatch power to the grid in the event of a decline in wind availability. Peak-load diesel and simple (open-cycle) gas plants and, to a much lesser degree,

[2] These are the current authors' calculations using values from Gross et al (2007). Although not given, total generating capacity is approximately 24.3 GW. However, there is no discussion in Gross et al. (2006, 2007) as to whether wind generating capacity simply replaces conventional generating capacity, yet this seems to be the logical assumption based on the discussion found in these sources. Our analysis suggests that this is a highly optimistic analysis of wind power.

combined-cycle natural gas plants are able to ramp up and down to some extent, but must sell any excess power to another operator, usually at low cost. With non-dispatchable wind power entering a grid, there is an economic cost because generators operate more often below their optimal efficiency ratings (less than their optimal instantaneous capacity factors). In addition, wind variability causes peak-load diesel and open-cycle gas plants to stop and start more frequently, which increases operating and maintenance (O&M) costs.

A suitable constrained optimization model of an electricity grid that assumes rational expectations (load and wind power availability are known beforehand) can be used to address these issues, including the need for additional reserves. Such a model should lead to similar policy outcomes and similar or lower predictions of costs than simply focusing on reserves. The only difference is that a grid optimization model takes explicit account of the need to balance output from existing generators on the grid (Prescott and van Kooten, 2007; Maddaloni et al., 2008b; Prescott et al., 2009). Costs of new transmission lines from wind assets to an existing grid are ignored for convenience.

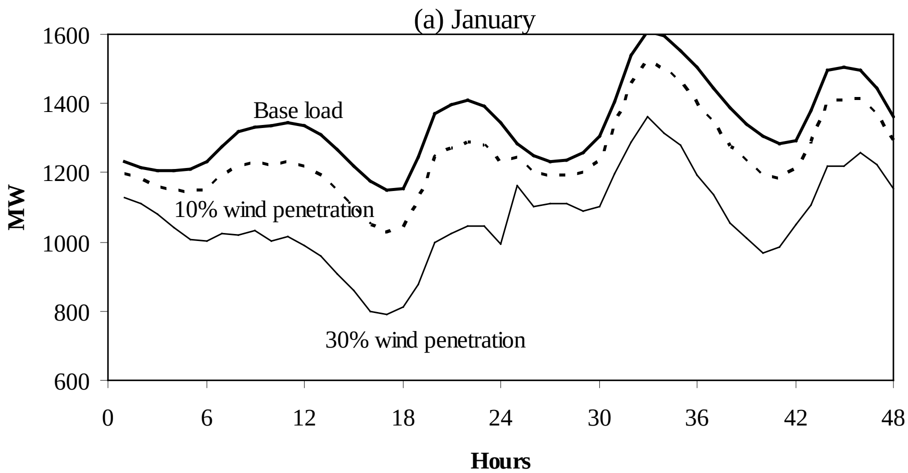
It is difficult to replace conventional generation capacity with non-dispatchable wind power while maintaining system reliability (Liik, et al., 2003; White, 2004; ESB, 2004; Lund, 2005; Pitt et al., 2005). To illustrate the problems and costs of reducing CO_2 emissions we examine integration of wind into three types of grids, which we denote 'high hydro', 'typical' and 'high fossil fuel'. The high hydro mix contains 60% hydroelectric generation with the other 40% allocated between nuclear and other thermal generating units. Typical is made up of 50% pulverized coal generation and 20% nuclear generation along with hydro and gas-fired units, while high fossil fuel also has 50% coal fired generation, some gas and hydro but no nuclear units (Table 7). We employ hourly load data from the ERCOT (Texas) system for

2007 (ERCOT, 2008), and wind data from sites located in western Canada. The ERCOT load data are standardized to a peak load of 2,500 MW (multiplying load data by 2,500 MW and dividing by ERCOT peak load of 62,101 MW). Wind power output consists of actual data from wind farms in southern Alberta and wind speed data for British Columbia (BC Hydro, 2004), converted to wind energy using a turbine manufacturer's power curves. Net load equals demand minus wind output, assuming wind penetration rates of 0%, 10% and 30%, where penetration is the ratio of installed wind capacity to peak load.

Table 7: Generating mixes as a percentage of total installed capacity

	Linear Model			Nonlinear Model		
Technology	High Hydro	Typical	High Fossil Fuel	Canada	United States	NW Power Pool
Hydroelectric	60%	8.4%	10%	58%	7%	43%
Nuclear	12%	20%	0%	12%	20%	5%
Pulverized coal	18%	50%	50%	19%	50%	12%
Combined-cycle NG (CCGT)	6%	18%	34%	6%	19%	38%
Other (biomass in linear model; oil in nonlinear model)	4%	3.6%	6%	5%	4%	2%
TOTAL	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

The costs and benefits of introducing wind power into an electricity grid depend on the generating mix considered. The constrained optimization model is linear, with constant marginal generation costs and simple capacity limits and ramping constraints, and takes into account fuel costs, operating and maintenance (O&M) costs and investment costs, as well as life-cycle CO_2 emissions. Linearity permits optimization over a full year or 8760 hours. Operating reserve requirements (regulating and contingency reserves) are ignored. Simulation results are provided in Figures 3–5, and these confirm earlier research by DeCarolis and Keith (2006), Pitt et al. (2005), ESB (2004), Lund (2005), and the Nordel Grid Group (2000).



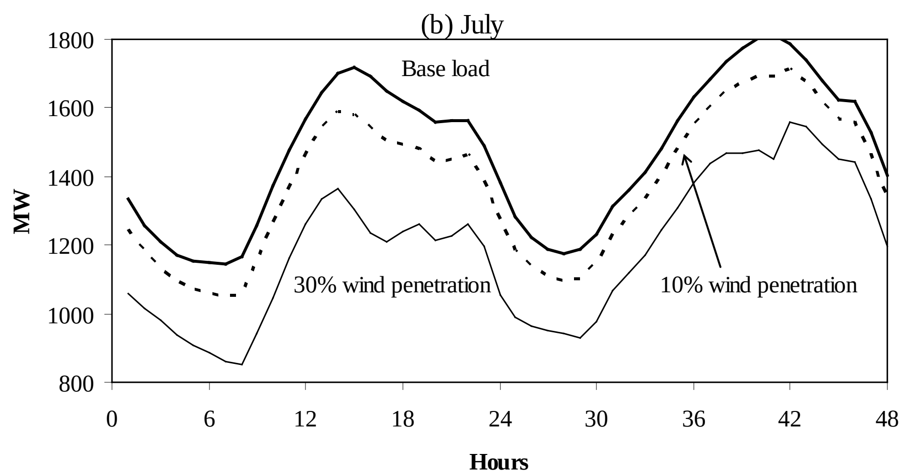
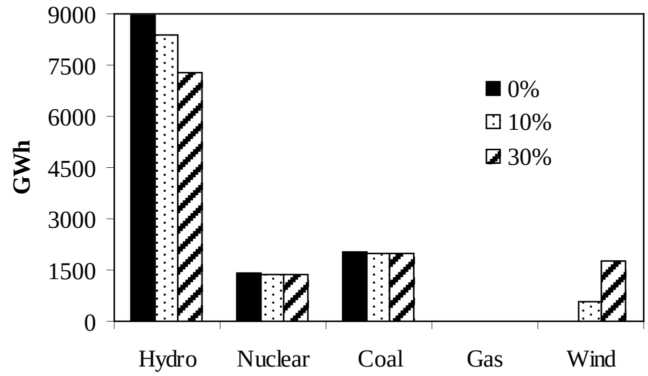
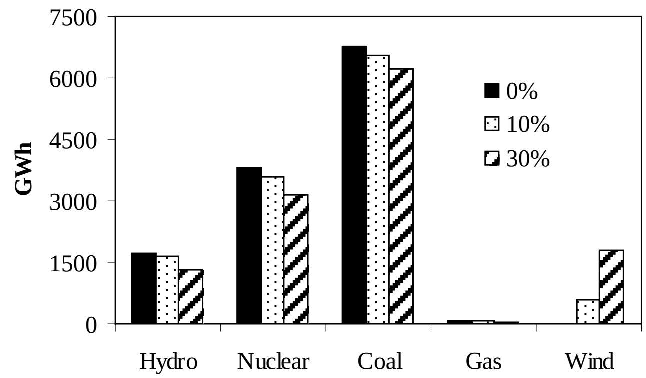


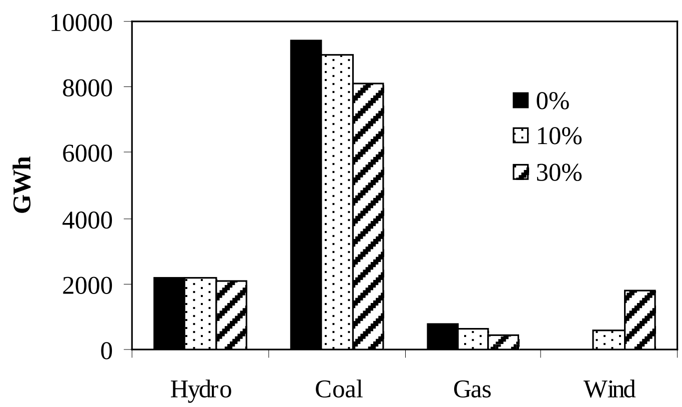
Figure 3: Load to be met by traditional generators for the first two days (48 hours) in (a) January and (b) July (adjusted ERCOT load data). Demand after non-dispatchable wind power has been subtracted has greater variability than the non-wind load, although the adjusted series still track the morning (0600-1200) and evening (1800-2300) peaks quite well. If a longer profile were chosen, the volatility would be even sharper.



(a) High hydro

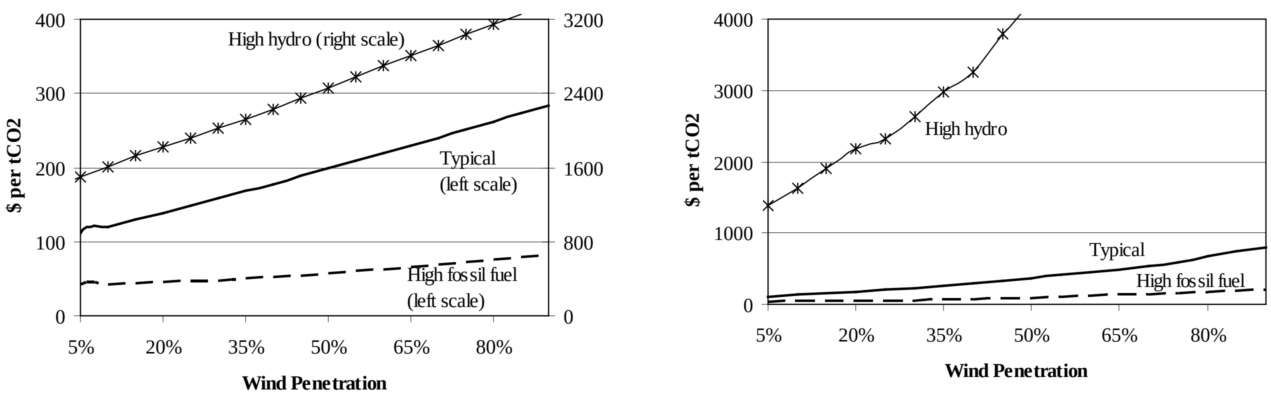


(b) Typical



(c) High fossil fuel

Figure 4: The effect of wind penetration varies according to the extant generating mix shown as output by generation type. (a) Hydropower adjusts instantaneously to changes in wind, enabling nuclear and coal base-load plants to operate at the same capacity as wind penetration increases. (b) In a mix with less hydro capacity, outputs of base-load nuclear and coal facilities vary and they operate at lower average capacity (lower capacity factor) as wind penetration increases. (c) In a fossil fuel generating mix, hydro's capacity factor changes least because almost all hydro capacity is utilized; hydro and gas adjust to short-term fluctuations in net load. Coal generation is affected by increasing wind penetration, leading to excess generation, because it cannot adjust quickly enough to changes in net load.



(a) Average Costs

(b) Marginal Costs

Figure 5: Average (a) and marginal (b) costs of reducing CO_2 emissions with wind power for high hydro, typical and high fossil fuel generating mixes. Wind penetration is normalized to peak demand. Results are based on a linear constrained optimization model. For integrating wind energy, the high hydro mix leads to the highest average and marginal costs, followed by the typical mix. Only for the fossil fuel mix are average and marginal costs below some $50 per tCO_2 emissions reduction, and then only up to a penetration of 20%. Nowhere are emission reduction costs below $30 per tCO_2.

Despite perfect foresight regarding wind availability, generators cannot adjust their output quickly enough to prevent unnecessary generation, unless there is sufficient hydro generating capacity. Hydroelectric units can be adjusted on extremely short notice. As a result of excess thermal generation, the reduction in CO_2 emissions associated with the integration of wind assets is also relatively small, and is largest for the fossil fuel mix. For 30% wind penetration, the largest reduction in emissions amounts to only 14.5% of the zero wind scenario, and then only for the fossil fuel mix; for the typical and high hydro mixes, CO_2 emissions are reduced by only 8.1% and 1.3% respectively. Clearly, the degree to which wind power is able to reduce CO_2 emissions depends on the amount of hydroelectric and nuclear generating capacity there is in the generating mix, as these emit little CO_2.

The average and marginal costs of reducing CO_2 emissions are lowest for the high fossil fuel mix and greatest for the high hydro mix, amounting to more than $1,000 per tCO_2

even for wind penetration rates as low as 5% (Table 8). This is the result of introducing zero emissions technology into a generation mix that already produces little CO_2. Thus any additional CO_2 reductions come at great cost. For a grid with mainly fossil-fuel units, emissions reductions can be produced at much lower marginal cost (\$42.86/tCO_2 vs. \$1,493.71/tCO_2 for 10% wind energy penetration). Electricity costs will increase as a result of wind penetration, by 16% to 73% for 10% wind penetration, and much more for higher penetration levels (Table 8).

Table 8: Marginal costs of reducing CO_2 emissions

Generation mix/ Wind penetration	Reducing emissions per tCO_2		Increase in costs per MWh	
	10%	30%	10%	30%
High hydro	$1,622.29	$2,639.25	73%	245%
Typical	$130.68	$229.38	26%	88%
Fossil Fuel	$43.79	$57.06	16%	58%

For comparison, Maddaloni et al. (2008b) investigated the integration of wind into an extant grid using a nonlinear constrained optimization model that permitted declining efficiency at below optimal operation of generators. As a result of computational restrictions, they could only run scenarios over two weeks (336 hours); they used representative winter and summer load and wind profiles. The generation mixes were typical of those found in Canada, the United States and the Pacific Northwest Power Pool (NWPP), but normalized to 2054 MW and not dissimilar from those used in the linear model (see Table 7). Results in Figure 6 suggest that wind can be integrated into a US or NWPP mix at a reasonable cost of reducing CO_2 emissions (say, lower than \$50 per tCO_2), but then only to a penetration of about 15% for the US mix but 50% for the NWPP mix.

Other studies find similar high costs of reducing CO_2 emissions, in contrast to the finding by USDOE (2008) that wind power could reduce CO_2 emissions at a cost of \$5.70/tCO_2. A German study by Rosen et al. (2007) found costs of reducing CO_2 emissions rise from €87.70/tCO_2 to €125.71/tCO_2 and then to €171.47/tCO_2 as wind power production increases from 12.0 TWh (6 GW installed capacity in 2000) to 34.9 TWh (17.3 GW 2005) and 50.4 TWh (22.4 GW 2010) corresponding to respective wind penetrations of about 8%, 23% and 29%.

The results presented above indicate that several factors must be aligned before wind energy can reduce system-wide CO_2 emissions at reasonable cost. These include the load and wind profiles, and crucially the existing generating mix into which wind power is to be integrated. Operating constraints for coal- and gas-fired base-load generation lead to overproduction of electricity during certain periods, because units cannot ramp up and down quickly enough when wind energy is available. This results in less emission reductions than anticipated. Wind integration into a system that has high nuclear and/or hydroelectric generating capacity might also see fewer CO_2 benefits than anticipated as wind displaces non-CO_2 emitting sources, despite the ability of some hydro facilities to fluctuate as quickly as wind. Hydro storage is an advantage, but not always. The research indicates that a high degree of wind penetrability is feasible (negative to low costs of reducing CO_2 emissions) for flexible grids such as the NWPP that have sufficient hydro for storage and relatively fast-responding gas plants that track changes in load minus non-dispatchable wind, while keeping base-load nuclear and coal power plants operating efficiently (with only minor changes in output).

Rather than allowing extant generators to vary their output, thus increasing system costs, an alternative policy is to make wind power dispatchable by requiring wind operators to reduce output (by ‘feathering’ wind turbines or simply stopping blades from rotating) whenever the grid operator is unable to absorb the extra electricity. In this case, output from base-load plants is effectively given precedence over wind generated power because such plants cannot be ramped up and down, the ramping costs are too great, and/or excess power cannot be stored or sold. (In Alberta, for example, further expansion of wind farms was permitted only after developers agreed to control power output so that wind power was no longer ‘must run’.) This policy makes investments in wind farms must less attractive and is usually unacceptable to environmental groups.

Finally, an argument used to minimize intermittency and storage concerns relates to the placement of wind farms. If wind farms are placed over a large geographic area, then, for the same installed wind power capacity, the output would be smoother than if it were to come from a wind farm at a single site. Therefore, to overcome variability, it is necessary to locate wind farms across as large a geographic areas as possible and integrate their combined output into a large grid. By establishing wind farms across the entire country, onshore and offshore, the United Kingdom hopes to minimize the problems associated with intermittency. Further, by connecting all countries of Europe and placing wind farms throughout the continent as well as in Britain and Ireland, the hope is to increase the ability to employ wind generated power. Unfortunately, as demonstrated by Oswald, Raine, and Ashraf-Ball (2008), large weather systems can influence the British Isles and the European continent simultaneously. They demonstrate that at 18:00 hours on February 2, 2006, electricity demand in the United Kingdom peaked, but wind power was zero (indeed wind farms added to the load at that time). At the same time, wind power output in Germany, Spain and Ireland was also extremely low – 4.3%, 2.2% and 10.6% of capacities, respectively. Thus, even a super grid with many wind farms scattered over a large landscape cannot avoid the problems associated with intermittency, including the need to manage delivery of power from various non-wind power generators.

7. Climate Change as a Driver of Wind Power Development

Much credit should go to climate change initiatives to promote wind energy over the past decade both in developed and developing countries. In the developed countries, fiscal policies and regulatory mandates, enacted to meet Kyoto commitments, have promoted wind power. In the developing countries, the clean development mechanism of the Kyoto Protocol has played a catalytic role. Various international organizations, particularly the World Bank Group and the United Nations' Development Program, have also contributed significantly to finance wind power projects through the Global Environmental Facility (GEF).

As seen in Table 6, many developed countries have set targets for developing wind power along with other renewable energy, considering their climate change mitigation obligations as well as other considerations, such as long-term energy security. For example, Australia is planning to install 10 GW of wind power capacity by 2020; Canada is planning to have 12 GW of wind capacity by 2016; Japan, Italy and Spain are planning to have respectively, 3 GW, 8 GW and 20 GW of wind power capacity by 2010.

In developing countries, the CDM has been playing an instrumental role in implementing wind power projects. By mid 2008, 144 wind power projects with a combined capacity of 6,070MW were registered under the CDM. An additional 308 projects with a combined capacity of 11,238MW are in the process of registration (see Table 8). While these projects are distributed across the globe, about 90% of the total projects with about 85% of the total capacity are concentrated in China and India. China alone accounts for more than 60% of total installed capacity. Mexico, South Korea and Brazil account for the bulk of the remaining projects. Wind power projects account for approximately 13% of the total CDM projects already registered or in the pipeline. In terms of GHG mitigation, these projects share 7% of annual potential (see Table 9). In addition to CDM projects, 16 wind energy projects were being implemented in economies in transition by mid 2008 under Kyoto's joint implementation mechanism (URC, 2008b).

Table 8: CDM wind projects as of June 2008

Country	Total projects (already registered and in process)		Registered projects	
	Number	Capacity (MW)	Number	Capacity (MW)
India	195	3,958	54	1,302
China	206	10,642	65	3,236
Mexico	11	1,222	5	798
South Korea	10	287	4	156
Brazil	7	436	4	166
Dominican Republic	3	173	1	65
Philippines	2	73	1	33
Morocco	2	70	2	70
Cyprus	2	44	2	44
Egypt	1	120	1	120
Panama	1	81	0	0
Mongolia	1	50	0	0
Jamaica	1	21	1	21
Costa Rica	1	20	1	20
Colombia	1	20	1	20
Israel	1	12	1	12
Argentina	1	11	1	11
Chile	1	19	0	0
Nicaragua	1	20	0	0
Vietnam	1	30	0	0
Ecuador	1	2	0	0
TOTAL	**450**	**17,308**	**144**	**6,071**

Source: URC (2008a).

Table 9: CDM projects registered and in the process of registration as of June 2008

Project type	Total (registered and in process)				Registered			
	Project		CERs		Project		CERs	
	No.	%	No.	%	No.	%	No.	%
Renewable	2,176	62	171.5	34	641	59	42.2	20
Wind	450	13	36.6	7	144	13	12.1	6
Hydro	926	26	89.5	18	208	19	14.3	7
Biomass	541	15	31.4	6	214	20	11.7	5
Biogas	226	6	10.8	2	64	6	2.3	1
Solar	20	0.6	0.6	0.1	4	0.4	0.04	0.02
Geothermal	12	0.3	2.4	0.5	6	0.6	1.5	0.7
Tidal	1	0.03	0.3	0.1	1	0.1	0.3	0.1
HFCs, PFCs & N2O reduction	82	2	128.8	26	50	5	114.1	53
Methane, Cement & Coal mine	558	16	89.4	18	232	21	36.8	17
Supply side Energy Efficiency	355	10	60.9	12	76	7	11.4	5
Demand side Energy Efficiency	175	5	6.3	1	49	5	1.5	0.7
Fuel switching	124	4	38.4	8	29	3	10.1	5
Afforestation & Reforestation	21	0.6	1.5	0.3	1	0.1	0.03	0.01
Transport	7	0.2	0.7	0.1	2	0.2	0.3	0.1
Total	3,498	100	497.6	100	1080	100	216.4	100

Note: CER refers to certified emission reduction units, 1 CER = 1 tons of CO_2 equivalent

Source: URC (2008a).

8. Conclusions and Final Remarks

This study presents the current status and future prospects of wind power at the global level, considering various aspects such as resource potential, installed capacity, economics, physical barriers, intermittency, grid interconnections, and policies related primarily to climate change. We find that global wind power generation capacity expanded rapidly from only 10 MW in 1980 to 94,124 MW by the end of 2007, with an average annual growth rate of about 40%. Despite the phenomenal growth of installed capacity, wind power still accounted for only 1% of global electricity supply as of 2007. Moreover, the distribution of installed capacity and ongoing investment are preponderantly concentrated in developed countries, with the exception of China and India. Existing studies estimate that wind power could account for 7% to 34% of the global electricity supply by 2050, and that the earth's wind resources could potentially contribute sufficient power to supply global energy needs. The ability to continue expansion of wind power will depend, however, on the specific circumstances facing a country or region, such as the generating mix of the grid to which wind will be connected, the distance between wind farms and the nearest grid connection, economic incentives, and institutional support. But it also depends on prices of fossil fuels, economic and political developments surrounding nuclear power, and the cost and availability of other renewable sources of energy.

Unlike fossil fuel generation, wind power faces a large number of technical, financial, institutional, market and other barriers. The intermittent nature of wind power and the relative remoteness of locations where wind resources normally exist are key technical barriers. Relatively higher upfront capital costs and lack of access to financing, especially in developing countries, are some key financial barriers. To overcome these barriers, many countries have introduced a variety of policy instruments, the most common of which are capital subsidies, tax incentives and feed-in tariffs. However, existing policy instruments alone are not in many cases sufficient to increase significantly the share of wind power in the global electricity supply mix. Unless the basic economic parameters underlying the expansion of wind power change dramatically in the near future, therefore, wind energy will not satisfy more than a few percent of total global electricity needs in the foreseeable future.

Climate change mitigation initiatives, particularly the Kyoto commitments and the flexibility mechanisms under the Kyoto Protocol, currently play instrumental roles in promoting wind power deployment. Kyoto obligations have caused many developed countries aggressively to pursue wind power development, while developing countries have actively developed wind power projects under Kyoto's clean development mechanism. As of June

2008, wind power projects with a combined capacity of about 6 GW had already been registered under the CDM and an additional 11 GW was in the process. Moreover, more stringent GHG mitigation targets beyond 2012 is likely further accelerate the expansion of wind power across the globe, but, again, this will depend on technological developments and economics pertaining to other renewable and non-renewable energy sources.

In the final analysis, however, it appears that the efficacy of introducing wind as a climate change mitigation strategy is unclear. For certain grid types (hydro and typical), the CO_2 emission reductions are small and the cost is substantial. Depending on the value of CO_2 emissions mitigation it might pay to introduce wind power into a high fossil fuel mix and it might even be advantageous to introduce some wind power into an existing typical generation mix. The benefit of integrating wind into a predominantly hydroelectric system is uncertain since emissions reductions are small while the per unit abatement cost of CO_2 is substantial. It appears that a knife-edge combination of factors is needed to ensure economic viability of wind energy.

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