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Wind Power Development

Economics and Policies

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Abstract

This study reviews the prospects of wind power at the global level. Existing studies indicate that the earth's wind energy supply potential significantly exceeds global energy demand. Yet, only 1 percent of the global electricity demand is currently derived from wind power despite 40 percent annual growth in wind generating capacity over the past 25 years. More than 98 percent of total current wind power capacity is installed in the developed countries plus China and India. It has been estimated that wind power could supply 7 to 34 percent of global electricity needs by 2050. However, wind power faces a large number of technical, economic, financial, institutional, market, and other barriers. To overcome these barriers, 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 countries and the Clean Development Mechanism in developing countries) have played a significant role in promoting wind power.

This paper—a product of the Environment and Energy Team, Development Research Group—is part of a larger effort in the department to study climate change and clean energy issues. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The author may be contacted at gtimilsina@worldbank.org.

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Wind Power Development: Economics and Policies

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1. Introduction

The global energy supply system faces challenges on three fronts: price volatility, energy security and the environment, particularly regarding local air pollution and global warming. A primary cause of these problems is the predominant share of fossil fuels in the global energy supply mix. Currently, fossil fuels account for more than 80 percent of the global energy supply and that share is not expected to change over the next 25 years under a business as usual scenario (IEA, 2008). To address these concerns, there would be a need to diversify the energy supply portfolio towards cleaner and more sustainable sources of energy, such as renewable energy (RE) (Ayres, 2008; Anderson and Winne, 2007). RE sources 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 countries have already set targets to increase the share of RE in their energy supply mix.[1] For example, the European Union (EU) has introduced an overall target of a 20 percent share of RE sources in energy consumption by 2020 (CEC, 2008). In China, RE sources are expected to account for 15 percent of the total primary energy supply by 2020 (Martinot, 2008).

Although most RE sources have exhibited strong growth recently, the deployment of wind power has significantly outpaced other RE sources with the exception of large hydro. During 2001-2007, 70 Gigawatts (GW) of wind generating capacity was installed globally, which is more than half of the added hydropower capacity (134 GW) and almost seven times as much as the amount of solar photovoltaic generating capacity installed during the same period (EPI, 2008). Still, the share of wind power in global energy supply is negligible. Moreover, the recent world energy outlook published by the International Energy Agency (IEA) projects that less than two percent of the globe’s energy supply will be met by wind power by 2030 (IEA, 2008). An obvious question is: Why is the contribution of wind energy to the global energy supply mix negligible currently and expected to remain very small in the near future? The answer rests with several factors, including technical, economic, financial and institutional barriers. To successfully implement wind power on a larger scale, it is

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[1] *RE targets in many countries are presented later in this paper.*

necessary to focus on policies and strategies to reduce market barriers and promote research and development to further reduce the costs of wind turbine technology. Advances in climate change mitigation negotiations also will strengthen the financial picture for wind, as would include wind strategies in policies addressing energy security.

The purpose of the current review is to examine these issues and provide insights concerning the future potential of wind power as a renewable energy source. Although there is a large volume of research in the field of wind power, the existing literature focuses more on engineering or technological aspects of wind energy. Hence, our review, unintentionally, has a somewhat engineering or technical flavor although our focus is on economic and policy issues despite the fact that such peer-reviewed research is still in its infancy.

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 options to overcome those barriers. This is followed by discussions on the intermittent 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.

2. Current Status of Wind Power Installations

Installed global wind generating capacity expanded rapidly from only 10 megawatts (MW) in 1980 to 94,124 MW of installed capacity by the end of 2007 (see Table 1).[2] 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; upon including China and India, this increased to 98.3% of global installed capacity. As indicated in Figure 1, 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.

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

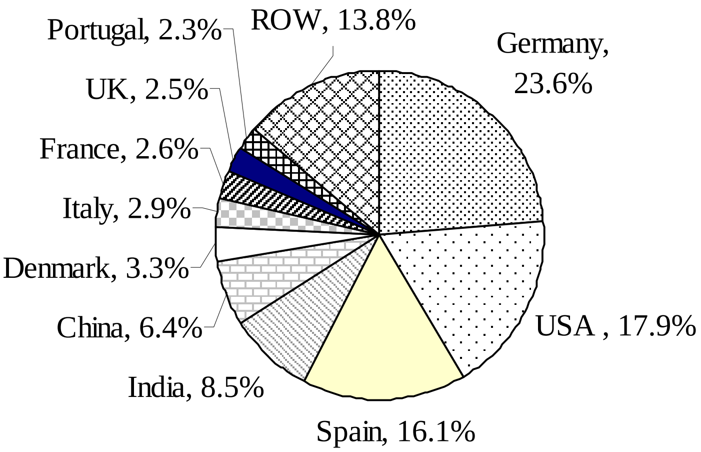
Table 1. Cumulative Installed Wind Power Capacity (MW), 1980-2007

Year	Germany	U.S.	Spain	India	China	Denmark	Other	Global
1980	0	8	0	0	0	2	n.a.	10
1981	0	18	0	0	0	7	n.a	25
1982	0	84	0	0	0	12	n.a	96
1983	0	254	0	0	0	20	n.a	274
1984	0	653	0	0	0	27	n.a	680
1985	0	945	0	0	0	50	25	1,020
1986	0	1,265	0	0	0	82	n.a	1347
1987	5	1,333	0	0	0	115	n.a	1,453
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	n.a	2278
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: EPI (2008)

Over the period 1980 to 2007, growth in wind generating capacity has averaged 44.4% per annum, although it has slowed to 27.4% since 1999. It is surprising that the 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 it registered very high growth rates in recent years, the current role of wind power in meeting global electricity demand is almost negligible as it accounts for only about 1% of the global electricity supply (IEA, 2008).

Figure 1. *Distribution of Global Installed Wind Capacity across Countries, 2007*



Source: Renewable Energy Industry (2008)

3. Resource Potential and Future Development Prospects

A number of studies provide estimates of the global potential of wind power generation (Archer and Jacobson, 2005; Global Wind Energy Council & Greenpeace International, 2006; IEA, 2008). Archer and Jacobson (2005) in particular argue that the earth has enough wind resources to meet current energy demand for all purposes (6995 to 10,177 Mtoe) and over seven times the world's current electricity capacity (1.6-1.8 TW). They arrive at this conclusion by analyzing approximately 7,500 surface stations and another 500 balloon-launch stations. More than 13% of all reporting stations experience mean annual wind speeds greater than the 6.9 meters per second (m/s) at a hub height of 80 m (i.e., wind power class 3 or greater), which they consider to be low cost wind power resources. 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 for fossil fuels, wind power has excellent potential for continued rapid deployment. A 2006 joint study by the Global Wind Energy Council (GWEC) and Greenpeace International (GI) 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; 15.6% in 2030 to 17.7% by 2050 under the moderate scenario; and 29.1% in 2030 up to 34.2% by 2050 under the advanced scenario. GWEC and GI (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 & GI (2006)

The projections of wind power development vary across studies based on the underlying assumptions and projections used in their models. In a 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. Under the ACT scenario, global wind power capacity is estimated to increase from 94 GW in 2007 to 1,360 GW in 2050. The capacity would increase 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 through wind by 2030. A study commissioned by the Department (USDOE, 2008) concluded that a 20% wind scenario in 2030, while ambitious, might prove feasible if certain challenges can be overcome. First, the U.S. would require 300 GW of wind power capacity to be installed 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, which 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 the 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, while 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 would also result in cumulative CO_2 reductions of more than 7,600 million metric tons (Mt of CO_2) 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 this is realistic, then wind energy development has a promising future in the United States.

4. Costs of Wind Power Generation

The costs of generating wind power depend to a large extent on wind resources, in particular, mean wind speed at hub height, the cost of turbines and related equipment, the proximity to a sufficiently strong transmission grid (i.e. the cost of grid extension and grid reinforcement), and the accessibility of the site. Other factors such as the existing generating mix, system load profiles, connections to grids in other countries/regions, electricity markets, system operating procedures, and land costs also have a significant impact on the costs of wind power generation. A large number of studies compare the costs of wind power with those of other electricity generation technologies (e.g., NEA/IEA, 2005; Kammen and Pacca, 2004; Lazard, 2008; CPUC, 2008; EIA, 2008; ESMAP/WB, 2008). Since electricity generation technologies vary significantly in terms of their investment requirements and operational characteristics, costs are converted to a level or base for comparison purposes, known as the levelized (or bus bar) cost of electricity generation. The levelized cost includes mainly investment or capital costs, operation and maintenance (O&M) costs, and fuel costs. While capital and fixed O&M costs are proportional to installed capacity, variable O&M and fuel costs are functions of electricity output.

Recent studies show that wind power can be competitive with conventional sources of electricity generation. A comparison of the levelized costs of various electricity generation technologies released by the California Public Utilities Commission on May 13, 2008 shows that wind power is one of the cheapest options with levelized cost of US$89.10/MWh (CPUC, 2008). Levelized costs per MWh expressed in 2008 US$ of other technologies examined by the Commissions are as follows: Supercritical Coal – \$106; Integrated Gasification Combined Cycle (IGCC) Coal – \$115; IGCC Coal with Carbon Capture & Storage (CCS) – \$173;

Biogas – $86; Gas Combined Cycle – $94; Geothermal – $102; Hydro – $105; Concentrating Solar Thermal (CSP) – $127; Nuclear – $153; and Biomass – $165. This study used fixed 2008 price for fuels instead of projected fuel prices and prices of fuels and materials were at their peak in that year. The costs do not include external costs such as carbon tax. [3]

Lazard (2008) also estimates that wind power is one of the cheapest options for generating electricity in the United States with levelized cost ranging from $44 per MWh to $91/MWh in 2008 dollars. For other generating technologies, Lazard (2008) estimates levelized cost ranges of (in 2008 US$ per MWh) $221-$334 for peak (open-cycle) gas, $104-$134 for IGCC, $98-$126 for nuclear, $74-$135 for advanced supercritical coal,[4] $73-$100 for Gas Combined Cycle, $109-$154 for solar PV (crystalline), $96-$124 for solar PV (thin film), $90-$145 for solar thermal, $115-$125 for fuel cell, $50-$94 for biomass, $50-$81 for landfill gas, and $42-$69 for geothermal. These estimates do not represent the true cost to society, however, because they include various government incentives, such as investment and production tax credits, accelerated asset depreciation and reduced tax rates. Further assumptions are 60% debt financing at 7% interest rate and 40% equity financing at 12% cost. Fuel prices used in the estimates are current fixed prices instead of projected prices. Since the study included taxes and subsidies, it deviates from cost-benefit analysis (CBA) methods.

All of the above cost calculations are for the United States. Moreover, those costs do not include transmission costs to connect electricity grids, which could be very high for wind power, especially where wind farms are remotely sited (e.g., offshore or mountainous regions). Also ignored are the increased costs of managing an electric grid when variable wind power enters into an existing generation mix.

The cost of wind power relative to other technologies varies significantly across countries and locations. ESMAP/World Bank (2008) estimates of the costs of electricity generation equipment for three countries, the United States, India and Romania, indicate that there are large variations in overnight construction costs across size of generation capacity

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[3] *Please refer to CPUC (2008) for detailed information on data and methodology used and assumptions made while estimating these costs.*

[4] *Upper range includes 90% carbon capture and storage.*

and locations/countries.[5] NEA and IEA (2005) calculate levelized costs of electricity generation technologies for various countries using data collected from a survey of system operators and power producers. Table 3 presents the range of levelized costs for various technologies. As can be seen from the table, the cost ranges are very wide for most of the technologies as electricity generation costs vary across countries. The table also presents the weights of different components of the levelized costs for different technologies. While capital is the main component for non-fossil fuel technologies, fuel costs account for more than half of the total costs with most fossil fuel based technologies.

The comparisons of levelized costs of electricity generation technologies significantly vary across existing studies for reasons related to fuel price projections, differences in material and labor costs across regions and studies, employment of different discount rates, and differences in exchange rates. In many instances, costs are not comparable across the studies due to a large divergence in their underlying assumptions and data. For example, cost estimates in the NEA and IEA (2005) study are expressed in 2003 values, whereas the cost estimates of CUPC (2008) and Lazard (2008) are expressed in 2008 dollars. Moreover, while the NEA and IEA study uses fuel price forecasts, CUPC (2008) and Lazard (2008) use current fuel prices and keep the price fixed over the life of the technology. Moreover, some studies follow financial analysis (e.g., CPUC, 2008; Lazard, 2008), whereas others (e.g., NEA & IEA (2005) follow economic analysis and hence the costs are not comparable across the studies.

The levelized costs presented in Table 3 do not include externality costs. Thus, the costs reported in Table 3 are not the total costs to the society. Moreover, if costs of externalities, such as costs of local air pollution, GHG emissions and other externalities (e.g., impacts of wind power on land use), are taken into appropriate account, the total costs of electricity generation technology also would change. Using a life cycle cost approach, some studies (e.g., Owen, 2004; Roth and Ambs, 2004) show that wind power could be as competitive as fossil fuels if environmental externalities are appropriately accounted for in calculating true social costs.

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[5] *However, the ESMAP & WB (2008) study does not calculate levelized costs of electricity generation.*

Table 3: Comparison of Levelized Costs of Wind Power with Other Technologies, 2003 $US/MWh

Plant Type	At 5% discount rate				At 10% discount rate			
	Levelized cost	Share in levelized cost (%)			Levelized cost	Share in levelized cost (%)		
	US$/MWh	Capital	O&M	Fuel	US$/MWh	Capital	O&M	Fuel
Wind (onshore)	31.1-92.3	79	21	0	46.1-144.2	85	15	0
Wind (offshore)	50.5-94.3	67	33	0	66.0-123.4	75	25	0
Solar thermal	165.5	77	23	0	269.4	86	14	0
Solar PV	120.6-484.8	96	5	0	209-1876	97	3	0
Small hydro	39.7-142.9	78	22	0	63.5-241.9	87	13	0
Large hydro	45.4	96	4	0	84.9	98	2	0
Nuclear	20.8-48.0	51	30	18	31.7-68.6	67	21	13
Lignite)	29.4-56.9	33	17	50	37.1-64.4	48	14	38
Coal	17.9-47.8	33	21	47	25.9-69.1	57	14	29
Coal (IGCC)	27.3-48.2	34	26	40	38.2-59.1	50	20	30
Gas (CCGT)	38.2-60.4	13	7	80	40.9-62.6	19	7	74
Gas (open)	46.70	8	4	88	49.0	13	4	83
CHP (Gas)	28.3-62.3	21	21	58	31.9-80.9	30	19	51
CHP (Coal)	25.0-36.8	41	34	25	34.8-46.9	56	26	18
CHP (other)	29.4-96.3	22	12	67	33.5-99.5	31	11	59
Biomass	37.3-85.2	36	24	40	50.3-100.5	52	18	30

Source: NEA & IEA (2005) Fuel costs of CHP plants are net of heat benefits. Weighted average costs of various plant sizes were considered while calculating the shares of capital, O&M and fuel costs. Estimates do not account for tax preferences, subsidies or environmental externalities. More detailed discussion of methods is found in NEA & IEA (2005).

Due to decreasing capital costs of wind power (see Neij, 2008), potentially increasing fossil fuel prices in the long term, and an increasing desire to account for environmental costs and benefits in electrical generation (e.g., via carbon credits), wind power is becoming more competitive with conventional resources for electricity generation. However, the direct cost of construction and operation is not the only factor to determine penetration of wind power into electricity grids. Other factors such as transmission access, intermittency, system reliability and grid characteristics significantly influence the contribution of wind power to a country's electricity supply system (see Sovacool, 2007).

5. Barriers to Wind Power Development

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

Perhaps the most critical technical barriers are lack of access to transmission lines, difficulties in 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 needed to assess the size of local wind resources. Available meteorological data are often inadequate for assessing wind resources, so mesoscale modeling based on satellite data with follow-up ground-based wind measurements and microscale wind modeling of the most promising areas are required to obtain 'bankable' wind projects. Otherwise, the uncertainty will discourage investors from developing wind power plants.

Equipment misspecification to comply with the power quality in the local grid also poses constraints. For example, at the early stage of wind power development in the Indian State of Gujrat, second-hand equipment 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 economic and financial barriers include high upfront capital costs and uncertainty regarding financial returns. This barrier is related to the lack of high quality wind resource data, thereby inhibiting access to financing. Since wind power is more capital intensive compared to conventional fossil-fuel fired generating technologies, the relatively high capital costs continue to be an obstacle to the adoption of wind power at the scale reflecting its technical potential. Moreover, the costs of constructing transmission lines from a wind farm to an electricity grid can be high, thereby making wind power generation less financially attractive relative to thermal power plants that can be constructed near existing transmission corridors or load centers at lower costs per kW of installed capacity.

In the case of off-grid wind power, 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.

Overall, wind power developers face difficulties in raising local equity due to the high level of technical complications and financial uncertainties (e.g., unfamiliar and potentially risky investment with uncertain returns). For the same reasons, wind power developers 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 option 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, which can be a substantial market barrier to wind power. Moreover, wind power plants generally tend to be smaller, and wind power producers have less clout in negotiating favorable terms with larger market players. Obviously, small projects face high transaction costs at every stage of the 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 (i.e., power purchase agreements) between the wind power developers and system operators (Beck and Martinot, 2004). Furthermore, many wind power projects are implemented as turn-key projects with bilateral or multilateral funding from developed 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. These types of problems 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).

6. Policy Instruments to Support Wind Energy

Many countries have developed strategies to reduce or overcome the barriers mentioned above. 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. Table 4 presents a summary of policies in 63 countries for which we could find information regarding their wind potential, renewable energy targets and current policies for increasing reliance on wind energy. Most of these 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.

As illustrated in Table 4, the policy instruments considered by various countries can be classified into three categories: (i) fiscal incentives, (ii) regulatory incentives, and (iii) other policies and programs. The key fiscal instruments include capital subsidies, tax incentives, feed-in tariffs, price guarantees, and tradable energy certificates. The main regulatory instruments introduced are mandatory targets, renewable energy portfolio/obligation standards. The other policies and programs include priority in dispatching, transmission access, and long-term contracts. 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 industrialized and nine developing nations provided other forms of aid (reduced taxes, tax credits, etc.) (Martinot, 2005). Moreover, 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). It is also clear that state ownership and public investment are often required to facilitate the development of wind power.

Table 4. Wind Potential, Policies and Wind 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 4. 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 4. 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 4. 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 4. 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).

Fiscal instruments are the policy instruments most commonly used to support wind power. 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.

7. Integration of Wind Power into Electricity Grids

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 (Scott 2007). Like solar PV or run-of-the-river hydro, wind power enters an electrical grid whenever there is an adequate amount of the resource available for generating electricity, but, unlike run-of-river hydro, the supply of wind power will fluctuate more than that of traditional thermal or large hydro generating sources that serve base load and are dispatched according to electricity demand. The intermittent nature of wind gives rise to two types of indirect costs: (i) the costs of additional system reserves to cover intermittency, and (ii) 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 system 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 et al, 2003, 2006; Kennedy, 2005). 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. Based on empirical wind data, they estimate that 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, $\sigma_w = 140$ MW for regulating and $\sigma_w = 930$ 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).[6] Although this might be considered a small addition to overall reserves, the financial implications are significant

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 non-dispatchable, or 'must run'. In that case, existing generators may need to operate at below optimal capacity, while ready to dispatch power to the grid in the event of a decline in wind

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[6] *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.*

availability. Peak-load diesel and simple (open-cycle) gas plants and, to a much lesser degree, combined-cycle gas turbine (CCGT) plants are able to ramp up and down to some extent in order to follow fluctuations in wind power availability. With non-dispatchable wind power entering a grid, there is an economic cost because peak-load and load-following generators operate more often below their optimal efficiency ratings (less than their optimal instantaneous capacity factors) – wind variability causes peak-load diesel and open-cycle gas plants to stop and start more frequently, which increases O&M costs. Furthermore, the grid operator is often required to sell excess power to another operator, usually at low cost. This is the case in Denmark, for example, where the ‘must-run’ requirement for both wind and CHP generated power requires the operator to export large amounts of electricity, especially at night when load is low and CHP and wind power might be high (Pitt et al., 2005).

This problem is exacerbated as wind penetration increases, particularly if the load remaining when wind generated power is subtracted exceeds the output of base-load power plants. Coal-fired power plants can ramp down only very slightly at night (when load is low and wind power might become available) so they can return to full operation during the day, although costs of operating below optimal capacity are generally high. (They can reduce output quickly only by venting steam, which can lower heat by hundreds of degrees Celsius, but at very high cost to equipment.) Nuclear power plants cannot ramp up and down over the time frames under consideration. Thus, whenever wind power is available excess power from base-load generators must be sold into another grid, perhaps displacing renewable energy production in some other jurisdiction (e.g., where no ‘must-run’ requirement exists).[7] If wind penetration is high, management of the grid may become especially problematic if wind resources are designated ‘must-run’ or non-dispatchable (Liik et al., 2003; Lund, 2005; Pitt et al., 2005). The indirect grid management costs are likely the highest costs associated with wind energy (Prescott et al., 2007; Maddaloni, Rowe and van Kooten, 2008a, 2008b), although this certainly warrants further investigation.

While this problem could be mitigated by storage of wind power, no viable large-scale storage systems are currently available. Because of the storage problem associated with the intermittency of supply, wind power is used most effectively in electricity grids that have

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[7] *Surprisingly, there are no studies of which we are aware that have examined the economics of displaced power in other jurisdictions.*

large hydropower capacity. In that case, water can be stored in reservoirs by withholding hydroelectricity from the grid when non-dispatchable wind power is produced, but releasing water and generating electricity when there is no wind power. This is precisely what happens with wind power in Denmark, where hydro reservoirs in Norway provide de facto storage (White, 2004; Lund, 2005), while lack of storage and/or connections to a larger market make wind power a less attractive option in Ireland and Estonia (Liik et al., 2003; ESB, 2004).

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 as it increases costs, and is usually unacceptable to environmental groups as it is perceived as a waste of renewable energy. Nonetheless, it might be the only way in which a grid can be managed to include wind power, especially as wind penetration levels increase.

One 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. In addition, 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.

The challenge to integrate wind energy into existing electricity grids depends on several factors, such as the availability of suitable sites for wind farms, the generation mix of the electricity grid, and government policies to support wind power. The best sites are those located on land where wind turbines least interfere with other land uses, where noise and visual externalities are minimal, and where the effect on wildlife is small. Sites should be scattered over a sufficiently large area so that they are not affected by the same weather patterns – so that the correlation of low wind among sites is minimal. Further, wind sites need to be connected to a transmission grid, and if such a grid does not exist in close proximity, the costs for deploying wind power become exceedingly large.

8. Climate Change and Wind Power

Climate change initiatives have done much 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 (UNDP), have also contributed significantly to the financing of wind power projects through the Global Environmental Facility (GEF).

As can be seen from Table 4, many developed countries have set targets for developing wind power along with other renewable energy sources. In choosing targets and policies, countries take into account a variety of considerations including climate change mitigation goals and obligations. 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 3 GW, 8 GW and 20 GW, respectively, of wind power capacity by 2010. In developing countries, the CDM has played an instrumental role in implementing wind power projects. By early 2009, 180 wind power projects with a combined capacity of 7,763 MW were registered under the CDM. An additional 441 projects with a combined capacity of 16,883 MW are in the process of registration (see Table 5). 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 almost 60% of total installed capacity. Mexico, South Korea and Brazil account for the bulk of the remaining projects.

Table 5. CDM Wind Projects

Country	Total projects (already registered and in process)		Registered projects	
	Projects (No.)	Capacity (MW)	Projects (No.)	Capacity (MW)
China	303	16,452	91	4,583
India	258	4,741	62	1,484
Mexico	12	1,272	6	958
Brazil	11	687	4	166
South Korea	10	314	4	156
Cyprus	4	207	2	44
Dominican Republic	3	173	1	65
Egypt	3	285	1	120
Philippines	2	73	1	33
Morocco	2	70	2	70
Costa Rica	2	69	1	20
Nicaragua	2	60	0	0
Panama	1	81	0	0
Mongolia	1	50	0	0
Jamaica	1	21	1	21
Colombia	1	20	1	20
Israel	1	12	1	12
Argentina	1	11	1	11
Chile	1	19	0	0
Vietnam	1	30	0	0
Ecuador	1	2	1	2
Total	621	24,646	180	7,763

Source: URC (2009a).

Wind power projects account for approximately 14% of the total CDM projects already registered or in the pipeline. In terms of GHG mitigation, these projects share 9% of annual potential (see Table 6). In addition to CDM projects, 18 wind energy projects were being implemented in economies in transition by early 2009 under Kyoto’s joint implementation mechanism (URC, 2009b).

Table 6. CDM Projects Registered and in the Process of Registration

Project type	Total (registered and in process)				Registered			
	Project		’000 CERs		Project		’000 CERs	
	No.	%	No.	%	No.	%	No.	%
Renewables	2,747	63	228,142	38	785	60	53,312	22
Hydro	1,150	26	118,015	20	287	22	19,722	8
Biomass energy	660	15	39,996	7	236	18	13,266	5
Wind	621	14	53,412	9	180	14	15,847	7
Biogas	275	6	13,242	2	70	5	2,528	1
Solar	27	1	704	0.1	4	0.3	43	0.02
Geothermal	13	0.3	2,457	0.4	7	1	1,590	1
Tidal	1	0.02	315	0.1	1	0.1	315	0.1
Methane, Cement & Coal mine	682	16	103,769	17	262	20	41,067	17
Supply-side energy efficiency	451	10	76,968	13	105	8	17,858	7
Demand-side energy efficiency	203	5	7,753	1	52	4	1,634	1
Fuel switching	139	3	44,226	7	35	3	13,077	5
HFCs, PFCs & N2O reduction	97	2	132,747	22	58	4	115,980	48
Afforestation & Reforestation	36	1	1,888	0.3	1	0.1	26	0.01
Transport	9	0.2	981	0.2	2	0.2	288	0.1
Total	4,364	100	596,473	100	1,300	100	243,242	100

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

Source: URC (2009a).

9. Concluding 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, financing, physical barriers, intermittency, grid interconnections, and policies related 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%. The growth is also facilitated by the improving economics of wind power as it is becoming increasingly competitive with traditional sources of electricity generation, such as coal, gas, hydro and nuclear. Despite the phenomenal growth of installed capacity, however, 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. The ability to continue expansion of wind power will depend, however, on the specific circumstances facing a country or region, such as the generation 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. It also depends on prices of improvements in wind technology, fossil fuels, economic and political developments surrounding nuclear power, and the cost and availability of other renewable sources of energy.

Wind power faces a large number of technical, financial, economic, 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 and economic 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 developed 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 adequate to increase significantly the share of wind power in the global electricity supply mix. To accomplish this, new and innovative policy instruments and strong institutional support would be necessary, as well as further advance in wind technology to lower its cost at larger scales of supply.

Climate change mitigation initiatives, particularly the Kyoto commitments and the flexibility mechanisms under the Kyoto Protocol, play pivotal roles in promoting wind power. In order to meet their Kyoto commitments, many developed countries have set domestic targets for wind power expansion, while developing countries are actively investing in wind power projects using funds available through the clean development mechanism. As of June 2008, wind power projects with a combined capacity of close to 8 GW had already been registered under the CDM and an additional almost 17 GW are in the process. Moreover, more stringent GHG mitigation targets beyond 2012 will likely help accelerate the expansion of wind power across the globe.

The paper does address the normative question of how much additional investment in wind capacity should be undertaken by developing countries, and through what means. We can observe that without efforts to lower institutional, regulatory and financing barriers, even cost-effective investments in wind capacity are impeded. At the same time, more fundamental technical and economic challenges need to be overcome in order for wind ultimately to displace significant fractions of fossil fuel electricity capacity in developing and developed countries. This could be accomplished through both further advances in the technology at a larger scale of deployment, and increases in the demand for wind technology as a consequence of a larger global market for CO_2 mitigation investments.

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