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Global wind power development: Economics and policies

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HIGHLIGHTS

- Global wind energy potential is enormous, yet the wind energy contribution is very small.
- Existing policies are boosting development of wind power.
- Costs of wind energy are higher than cost of fossil-based energies.
- Reasonable premiums for climate change mitigation substantially promote wind power.
- Intermittency is the key challenge to future development of wind power.

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ABSTRACT

Existing literature indicates that theoretically, the earth's wind energy supply potential significantly exceeds global energy demand. Yet, only 2–3% of global electricity demand is currently derived from wind power despite 27% annual growth in wind generating capacity over the last 17 years. More than 95% of total current wind power capacity is installed in the developed countries plus China and India. Our analysis shows that the economic competitiveness of wind power varies at wider range across countries or locations. A climate change damage cost of US\$20/tCO_2 imposed to fossil fuels would make onshore wind competitive to all fossil fuels for power generation; however, the same would not happen to offshore wind, with few exceptions, even if the damage cost is increased to US\$100/tCO_2. To overcome a large number of technical, financial, institutional, market and other barriers to wind power, 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, climate change mitigation policies, such as the Clean Development Mechanism, have played a pivotal role in promoting wind power. Despite these policies, intermittency, the main technical constraint, could remain as the major challenge to the future growth of wind power.

1. Introduction

The greatest challenges to global energy supply relate to energy supply security, price volatility, and the need to address greenhouse gas emissions that contribute to climate change. The primary cause of these problems is the predominant share of fossil fuels in the supply mix. Currently, fossil fuels account for more than 80% of global energy supply and that share is not expected to change over the next 25 years under a business as usual scenario (OECD/IEA, 2012). If reliance on fossil fuels is to be reduced, it is necessary to diversify the energy supply portfolio towards cleaner and more sustainable sources of energy, particularly renewable energy (RE) (Anderson and Winne, 2007; Ayres, 2008). RE sources include large-scale hydro, small-scale run-of-river hydro, wind, tidal, solar, wave, municipal solid wastes, geothermal and biomass for the generation of electricity and space heating, and biofuels (bioethanol, biomethanol and biodiesel) for transportation. Some countries have already set targets to increase the share of RE in their energy supply mix. For example, the European Union (EU) has introduced an overall target of a 20% share of RE sources in energy consumption by 2020 (Commission of the European Communities (CEC), 2008), while RE sources are expected to account for 15% of China's total primary energy supply by 2020 (REN21, 2012).

Although most RE sources have exhibited strong growth in terms of installed capacity in the recent years, the deployment of wind power has significantly outpaced other RE sources with the exception of large hydro. During 2004–2011, 190 gigawatts (GW) of wind generating capacity were installed globally, which is three quarters of the added hydropower capacity (250 GW) and almost

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three times as much as the amount of solar photovoltaic generating capacity (66 GW) installed during the same period (REN21, 2005, 2012). Yet, the share of wind energy in global energy supply remains negligible. Moreover, the recent world energy outlook published by the International Energy Agency projects that a mere 5% of the globe's electricity generation will be met by wind power by 2035 (OECD/IEA, 2012). An obvious question is: Why is the contribution of wind energy to the global energy supply mix currently so small, and expected to remain so in the foreseeable future? The answer is simply that the full economic costs of providing wind power are greater than those associated with traditional electricity generating types. The standard economic solution is that society must subsidize wind-power generation and related R&D activities, and tax fossil fuel generating sources, if it desires a greater role for wind in the generation mix; these policies are required to overcome existing technical, financial and institutional barriers to wind power. The purpose of the current review is to examine the costs of wind power and provide insights concerning its potential as a renewable energy source. It is to determine if the standard economic approach will suffice.

The literature examining the integration of wind power into electricity grids focuses primarily on engineering or technological aspects, although economists have also begun to make inroads into this question. Even so, while we focus on economic and policy issues, the discussion has a technical flavour. There exists a growing literature that addresses policy issues related to wind power development (e.g., Blanco, 2009; Lewis and Wiser, 2007; Liao et al., 2010; Scorah et al., 2012; van Kooten et al., 2013). While a consensus regarding the major problems of wind power – intermittency, storage, externalities, et cetera – is slowly emerging, it is useful at this stage to take stock of what is currently known. To do so, we present a comprehensive analysis of the economics of wind power using data from most publically available sources.

The paper is organized as follows: The status of wind power installation and a review of the global wind energy potential and future development prospects are provided in Section 2. We then analyze the direct costs of wind power generation and discuss various types of indirect costs associated with wind power development in Section 3. Relevant policy instruments to overcome key barriers to wind power development are explored in Section 4. The role of climate change mitigation initiatives to promote wind power is discussed in Section 5. We conclude in Section 6 with some summary observations.

2. Current status and future potential of wind power development

Installed global wind generating capacity expanded rapidly from only 10 MW (MW) in 1980 to 282 gigawatts (GW) of installed capacity by the end of 2012 (see Table 1).[1] At the end of 2012, Europe and North America accounted for more than 60% of global wind power capacity. Overall, developed countries plus China and India accounted for over 95% of global installed capacity. With the exception of China and India, 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. By 2010, wind turbines had been installed in at least 83 countries (ESMAP/WB, 2011). Over the period 1996 to 2012, growth in global wind generating capacity averaged 27% per annum (GWEC, 2013). Despite high growth rates in recent years, the current role of wind power in meeting global electricity demand remains small, accounting for about 2–3% of the global electricity supply (REN21, 2012).

Table 1
Cumulative installed wind power capacity (MW), 1980–2012.
Source: EPI (2008), GWEC (2013).

Year	Germany	U.S.	Spain	India	China	Denmark	Other	Global
1980	0	8	0	0	0	2	n.a.	10
1990	62	1,484	0	0	0	343	41	1,930
2000	6,104	2,578	2,235	1,220	346	2,300	2,617	17,400
2012	31,332	60,007	22,796	18,421	75,564	4,162	70,200	282,482

A number of studies provide estimates of the global potential of wind power generation (Archer and Jacobson, 2005; IEAWind, 2011), but they examine only the physical viability of wind power based on wind availability at various sites while ignoring many economic aspects. Wind power development is driven almost entirely by concerns about climate change and energy supply security (Narbel, 2013). While energy security has been highlighted as an issue in the U.S., for example, most countries can generate electricity from ubiquitous domestic coal resources or import coal from various stable countries (e.g., Australia, Canada, U.S.); alternatively, they can rely on nuclear energy (e.g., France) or increasingly available non-conventional natural gas. Indeed, the recent revolution in non-conventional gas has greatly reduced U.S. emissions of CO_2 as cheap gas has replaced coal in generating electricity. However, the reduction in gas prices has made wind power relatively less attractive to investors than previously. Further, prices of other renewable energy sources and technological developments in the nuclear industry, transportation and other sectors that influence energy prices are downplayed or assumed to favor wind power development (e.g., electric vehicles).

What then are the factors that favor wind? Archer and Jacobson (2005) argue that global wind resources are potentially adequate to meet current energy demand for all purposes (estimated by the authors between 6995 Mtoe and 10,177 Mtoe), and more than seven times the world's electricity capacity in 2000 (1.6–1.8 TW). They arrive at this conclusion by analyzing approximately 7500 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 m/s (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 Australian island of Tasmania, the Great Lakes region, and the northeastern and northwestern coasts of North America have the strongest wind power potential. If turbines were set up in all regions with wind speeds greater than 6.9 m/s, they would generate 72 TW of electricity (54,000 Mtoe). While wind turbines could not possibly be placed in every region identified by the authors, developing even 25% of those sites could satisfy current world energy consumption. Similarly, a study initiated by the United Nations' Environment Program (UNEP) estimated that the wind power potential in 19 African countries could reach 53 TW in those countries alone (InWEnt Consulting, 2004).

In the same vein, the International Energy Agency (OECD/IEA, 2012) estimates wind power development potential under three scenarios that are differentiated only by assumed future government policies. In the first scenario where policies already in place are maintained, global wind power electricity generation is estimated to increase from 342 TW h in 2010 to 2151 TW h by 2035, which corresponds to 5% of global electricity supply from all sources. In the second scenario (the *New Policies* scenario), governments implement the commitments and plans that have been announced; in this case, wind power output could reach

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

2681 TW h/yr by 2035 (8% of global electricity production). In the last scenario, atmospheric CO_2 concentration is limited to 450 ppm; then global electricity generation from wind power is projected to rise to 4281 TW h/yr by 2035, or more than 13% of global electricity supply. In its *New Policies* scenario, the IEA expects wind power production to grow significantly in OECD countries and in emerging economies such as China and India. Although installed onshore wind power capacity currently dominates, by 2035 some 16% of wind power capacity is expected to be offshore. However, the projections eschew economics entirely and are based solely on projections of current trends in wind power development. Indeed, contrary to economic theory and practice, the IEA study assumes that the global capacity factor of wind farms (=average annual production divided by 24 h per day times 365 days per year times the rated capacity of the wind farm) increases with installed capacity.[2]

Further, a U.S. Department of Energy study (USDOE, 2008) explores the possibility of supplying 20% of the nation's total electricity demand with wind by 2030. It found that, to meet such an ambitious target, the U.S. would require 300 GW of wind power capacity to be installed by 2030, which is five times the 2012 capacity of about 60 GW. It would require construction of more than 20,000 km of high-voltage transmission lines. Such construction is opposed not only by residents who do not wish high-voltage power lines to traverse their neighborhoods, but by several states because it would increase their electricity rates (as such a network would tend to equalize rates across regions). The USDOE study estimates that 600 GW of wind generating capacity could be installed at a cost of \$60–\$100/MW h, 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 technical innovations are expected to reduce actual costs as well. Overall, the USDOE (2008) estimates that the 20% wind scenario would result in US\$43 billion in incremental cost, but would reduce cumulative CO_2 emissions by more than 7.6 billion metric tons ($GtCO_2$) by 2030, or at a cost of about \$5.70 per ton of CO_2 (tCO_2). If this is realistic, then wind energy development has a promising future in the United States. As demonstrated later, this is likely an overly optimistic view of the costs of reducing CO_2 emissions.

Finally, the European Wind Power Agency (EWEA, 2011) expects 400 GW of wind energy capacity to be operational in Europe by 2030, which corresponds to wind power supplying over 28% of all European electricity production. Of this amount, onshore wind capacity would account for 250 GW (101 GW in 2012) and offshore wind capacity for 150 GW (5 GW in 2012). In the analysis, a carbon price of €40/tCO_2 (€4/tCO2 in May 2013) was assumed, and a fuel cost equivalent to US\$108.20/bbl of oil. The EWEA estimates that wind energy could cover 50% of the total European electricity demand in 2050. If the estimates are considered conservative, they exceed IEA's most enthusiastic estimates by over 36% for 2030.

3. Costs of wind power generation

The total wind power generation cost to society consists of (i) direct costs, (ii) indirect costs, and (iii) externality costs. The direct cost is the pure economic cost from the perspective of a private investor, and consists of capital costs and operating and maintenance (O&M) costs. The costs of wind power depend to a large extent on the wind resources at a particular site, namely, mean wind speed and the distribution of wind speed at hub height. These determine the capacity factor of the turbines at the site, which in turn impacts the economics of the wind development at that site. Because off-shore sites usually have a higher capacity factor, the EWEA (2009) estimates that coastal areas can be up to 36% less costly compared to low-lying on-shore wind sites. Direct costs include the costs of turbines and related equipment, construction costs, site purchase or rental, site access costs (e.g. road construction and preparation), and construction of transmission infrastructure. It also includes operating costs and routine maintenance and replacement costs.

The indirect costs are related to the nature of wind power generation and its integration into the power grid. Indirect costs depend on a host of factors, including the existing generating mix, system load profiles, connectivity to grids in other countries/regions, electricity markets, system operating procedures, available storage (e.g., hydroelectric dams), and the turbulence effects from other turbines and structures. These factors vary greatly from one location to another, and have a significant impact on the overall costs of wind power generation. Finally, there are the externality or spillover costs related to noise pollution, adverse health effects, loss of visual amenities, impacts on wildlife, falling ice, and so on. As discussed in this section, electricity generation technologies are not generally compared on the basis of their full costs. This is because the quantification of indirect and externality costs are location and system dependent. Moreover, estimation of indirect and externalities are associated with a large number of uncertainties and there are no universally accepted methods for estimating them. As a result, we too discuss the different cost components separately.

3.1. Direct costs

A major challenge for economic analysis of power generation technologies is the variation in cost data across technologies, plant size, country and time. The analysis presented here illustrates the potential competitiveness of wind energy with other technologies. Since electricity generation technologies vary significantly in terms of their investment requirements and operational characteristics, costs are converted to the same basis for comparison purposes, usually the levelized (or bus bar) cost of electricity (*LCOE*) generation.[3] The following approach has been adopted to calculate the *LCOE*:

$$LCOE = \sum_{i=1}^{K} \frac{OC/K}{(1+r)^i} + \sum_{j=K}^{T} \frac{(FOMC/CF \times 8760) + VOMC + F}{(1+r)^j}$$

where *OC* is the overnight construction cost, or the cost of all material, labor, fuel, et cetera needed to construct the facility if that cost were occurred at a single point in time; *K* is the time required to build the facility (construction costs are spread evenly over the construction period); *T* is the economic life of the plant; and *r* is the discount rate, *FOMC* refers to the annual fixed operating and maintenance costs that do not depend on output, *CF* is the capacity factor, *VOMC* is the variable (output dependent) O&M costs, and *F* are fuel costs that are also output dependent.

We take data from various sources including CPUC (2008), EIA (2008), Lazard (2011) and NEA/IEA (2010). The data are available for different years, so we adjusted them using the GDP deflator and expressed them in 2008 values. Moreover, the existing calculations of *LCOE* for a technology vary across studies as they use different economic lives, capacity factors and discount rates.

[2] The global capacity factor for wind farms is a disappointing 19.6% (see, as viewed October 25, 2011: http://lightbucket.wordpress.com/2008/03/13/the-capacity-factor-of-wind-power/).

[3] The levelized cost includes capital costs, 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.

Table 2
Key data used in economic analysis (US$2008).

Technology		Overnight construction cost (US$/kW)	Plant economic life (years)	Capacity factor (%)	Source
Wind (onshore)	Min	1283	20	41	Lazard
	Max	3716	25	23	NEA/IEA
Wind (offshore)	Min	3953	25	43	NEA/IEA
	Max	6083	25	37	NEA/IEA
Solar PV	Min	2878	20	27	Lazard
	Max	6592	25	16	NEA/IEA
Solar CSP	Min	5527	20	43	Lazard
	Max	6416	20	26	Lazard
Gas CC	Min	538	30	85	NEA/IEA
	Max	1549	30	85	NEA/IEA
Hydro	Min	896	80	57	NEA/IEA
	Max	3414	80	40	NEA/IEA
IGCC w CCS[a]	Min	4194	40	85	NEA/IEA
	Max	5182	40	75	Lazard
Supercritical coal[b]	Min	602	40	85	NEA/IEA
	Max	8290	40	93	Lazard
Nuclear	Min	1556	60	85	NEA/IEA
	Max	5863	60	85	NEA/IEA

[a] IGCC with carbon capture and storage.
[b] Supercritical coal.

Some studies account for financial costs (e.g., taxes and subsidies) (CPUC, 2008; Lazard, 2011), while others include only economic costs (NEA/IEA, 2010). Therefore, we have taken the maximum and minimum values of overnight construction costs for each technology considered here from the existing studies to reflect the variations in overnight construction costs, along with the corresponding O&M and fuel costs, and we applied a uniform 10% discount rate and 2.5% fuel price and O&M costs escalation rate to cost data from all the studies. Since our focus is on economic analysis, taxes, subsidies or any types of capacity credits are excluded. Please see Table 2 for key data used in the economic analysis.

Fig. 1 presents the results of the levelized cost analysis.[4] Although wind energy costs have come down considerably and continue to fall, the levelized costs of onshore wind power and especially offshore wind power are still high compared to conventional technologies for electricity generation. For example, the minimum levelized costs values for wind power (US$58/MW h for onshore wind power and US$160/MW h for offshore wind power) shows that grid parity has not been reached when compared to the levelized costs of supercritical coal without carbon capture and storage (US$41/MW h) and with gas CC (US$47/MW h). Compared to the other clean energy technologies, onshore wind is much more competitive with nuclear power and clearly cheaper than solar technologies. Hydropower remains, however, more competitive. At present, offshore wind remains expensive, although optimally located wind farms outcompete the best solar projects.

The difference between the minimum and maximum values for the levelized costs of the various technologies is due to large variations in overnight construction costs and to different capacity factors. For example, the overnight construction costs of onshore wind farms vary from US$1283/kW (Lazard, 2011) to US$3716/kW (NEA/IEA, 2010). Similarly, the overnight construction costs of offshore wind projects vary from US$3953/kW to US$6083/kW (NEA/IEA, 2010). For thermal and hydro power plants, the construction periods and economic plant lives vary considerably.

The contributions of various cost components (e.g., capital, O&M and fuel costs) to levelized costs also differ across technologies. While capital costs account for more than 80% of the levelized costs for renewable energy technologies, they generally account for less than 60% in conventional fossil fuel technologies (e.g., coal, gas combined cycle). Fuel costs are the major components in most fossil fuel technologies, but, as noted earlier, these have changed considerably in the past several years, particularly in the United States.

The direct costs of wind power relative to other technologies vary significantly across countries and locations. ESMAP/WB (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 and location.[5]

Some direct costs that are often ignored in these studies are the transaction costs. These are normally higher for wind power compared to traditional electricity generation technologies, such as coal and gas, because of higher technical and financial uncertainties with wind. As a result, commercial banks may charge higher interest rates as a result. Wind turbines need to be placed across a broad landscape and there are added costs of negotiating rental agreements with landowners, both related to the placement of turbines and, importantly, obtaining access for transmission lines. Moreover, wind power plants generally tend to be small, and so wind power producers have less clout in negotiating favourable terms with larger market players. Obviously, small projects face high transaction costs at every stage of the project development cycle.

In many countries, there is a general lack of economic institutions for facilitating power purchase agreements between wind power developers and system operators (Beck and Martinot, 2004). Furthermore, many wind power projects in developing countries 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 increased O&M costs. These types of problems could eventually lead to a loss of future interest in small-scale wind power development in remote villages (UNEP, 2001).

3.2. Indirect costs

Indirect costs refer to the operating costs imposed on the system as a whole when intermittent wind power enters into an electricity grid. Intermittency results in indirect costs related to the need for additional system reserves (e.g., see DeCarolis and Keith, 2005; Gross et al., 2007), and the extra costs associated with balancing or managing an electricity system when power from one (or more) generation sources fluctuates to accommodate intermittent wind (e.g., see Prescott and van Kooten, 2009; Scorah et al., 2012; van Kooten, 2010). The issue can be illustrated with the aid of Fig. 2.

Assume generators bid in advance to produce a certain amount of electricity at a particular price based on their expected marginal costs at the time they are to deliver power to the grid. The system operator uses this to create an economic merit order or supply

[4] Note that LCOE represents a snap-shot of cost comparison of electricity generation technology from a given time point (year). The relative cost competitiveness of these technologies would change if the analysis is carried out at another time point (e.g., next year or so). This is because the cost elements e.g., capital costs, fuel prices, efficiency of technologies etc. could change differently for different technologies. For example, future costs of solar and offshore wind might decrease due to technological innovation, whereas costs of thermal technologies may increase as fuel price always have increasing trend in the long run.

[5] As noted above, overnight construction costs ignore interest rates as it is assumed that the generating facility is literally built overnight. Therefore, they are not a good means of comparison. The ESMAP/WB (2008) study does not calculate levelized costs of electricity generation.

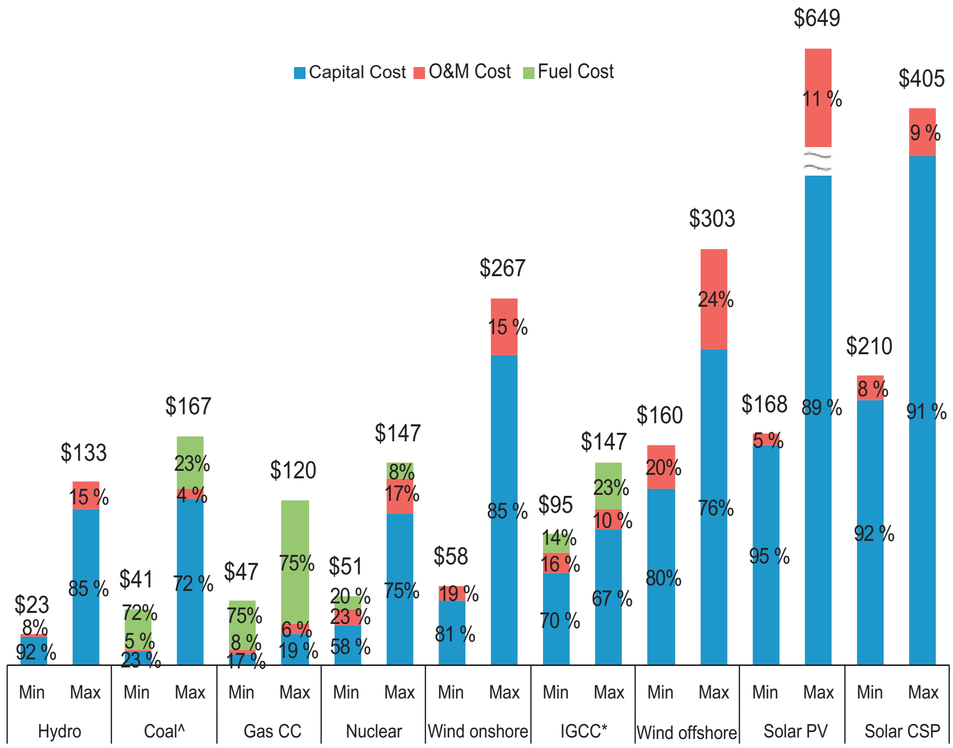

Fig. 1. Levelized cost of electricity generation by technology (2008US$/MW h) *Note*: * Coal IGCC with carbon capture and storage. ^ Supercritical coal.

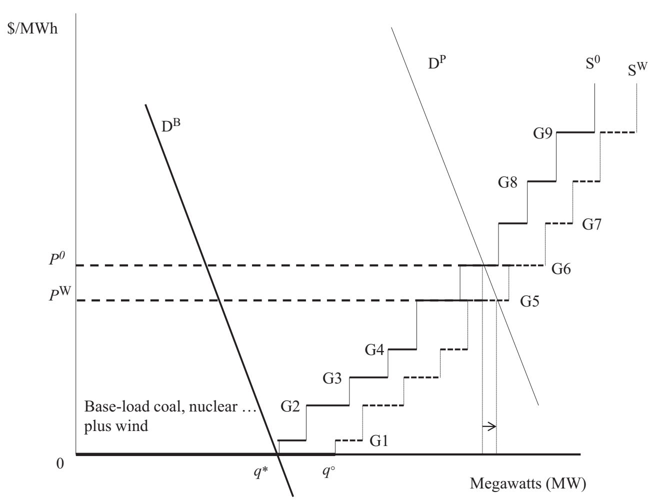

Fig. 2. Introduction of wind power into an electricity grid.

curve as indicated in the figure.[6] Base-load coal, nuclear and combined-cycle gas turbine (CCGT) generators will bid in at a price of zero to ensure that they are not taken off line. This is because, in general, base-load generators wish to ensure that their output is taken to avoid high costs associated with ramping constraints—they simply cannot ramp their power production up and down very quickly. Other generators can ramp at various rates, encounter different fuel costs, and so on, with these factors leading them to bid in their power at various prices. Thus, generator G1 has a lower marginal operating cost than G2, and so on.

Consider the case where no wind enters the system. Suppose that the supply of electricity at a given hour is given by S^0. If the demand at that hour is high, say D^P where P denotes a peak-time of day, generators G1 through G6 will be asked to deliver power to the grid, with the price for that hour, P^0, determined by the marginal cost of generator G6.[7] (All generators in the system, including base-load power plants receive P^0.) If the demand for that hour is at its lowest, say D^B, then only the base-load generators will be engaged, and G1 through G9 left idle. Base-load capacity is given by q^*.

It is easy to see how wind destabilizes the system. Assume that wind is non-dispatchable—it is 'must run' so any wind power that is produced must be accepted by the system operator. If an amount q^*q^0 wind power enters the grid, it shifts the supply curve in Fig. 2 to the right, from S^0 to S^W. Now, with demand curve D^P, it is no longer G6 that is the marginal producer of electricity; rather, it is the plant with a lower marginal cost, G5. The market clearing price of electricity for that hour falls from P^0 to P^W. The introduction of wind power lowers the price of electricity, which will induce consumers to purchase more of it (as indicated by the arrow).

What does one do with the wind energy q^*q^0 if the demand in a given hour is D^B. Clearly, either the wind must be curtailed (wasted) or base-load output reduced. Base-load hydropower can easily be reduced, but this is not the case in a system characterized by significant base-load thermal generating capacity. If q^*q^0 could be reliably produced in every period, so it can be considered part of base load production, then some thermal base-load capacity becomes redundant and can be eliminated—an ideal outcome especially if it is coal-fired capacity that is eliminated. However,

[6] See van Kooten (2013a, pp.417–422) for more details about the market merit order and the disruption caused by intermittent wind power entering a grid.

[7] This assumes G6 can deliver part of its bid-in power; if not, G6 will be bypassed for G7 and the hourly price will rise accordingly.

wind generated power is not reliable and thus cannot replace thermal base-load capacity.

Suppose base load capacity is reduced by the amount q^*q^0. Whenever wind power output is less than q^*q^0, this has the effect of shifting the supply curve in Fig. 2 to the left, thereby increasing market price; when wind power output increases to q^*q^0, say, price falls. Thus, the effect of wind farms is to increase price volatility if there is insufficient thermal base-load capacity in the system; if thermal base-load capacity remains, electricity prices will generally be lower, but base-load plants will need to ramp up or down more often if wind energy is non-dispatchable, which will increase their operating costs (van Kooten 2010). Alternatively, if wind is considered dispatchable, wind will need to be curtailed or wasted.

The situation might be different in a system with significant hydroelectric capacity, because hydropower can provide base-load power and serve the peak load and reserve markets. The presence of significant hydro capacity enables a system to absorb wind power that might overwhelm the ability of a system with a high thermal capacity in the generating mix to absorb it, or raise system costs by too much in doing so. That is, the existence of hydro reservoirs enables a system to store wind energy that would be wasted in systems lacking hydro generating capacity in the mix. However, there must be times when this stored wind energy is required to meet load, perhaps at peak load times.

Now consider some estimates of the indirect costs. Suppose that wind can contribute 10% of load at any given time, but that it could potentially contribute nothing some 20 min later. If the load is 8000 MW at any given instance, the intermittent event is equivalent to the loss of a generator with a capacity of 800 MW. Operating procedures require a system operator to be able to have adequate reserves in place to cover the loss of the largest generating unit in the system. If the largest generator in the system has a capacity of 450 MW, then it is necessary to increase reserves by 450 MW to meet the contingent wind event—loss of wind power. The cost of doing this is equal to the direct cost of building such capacity and the variable costs of retaining it in a reserve position. These costs are not inconsequential because payments to keep a generator of only 100 MW-capacity in reserve could run hundreds of thousands of dollars per day. It is also important to notice that, because wind power reduces the overall prices received by generators (see Fig. 2), there is much less incentive to invest in generating capacity.

In addition to the costs of reserves, the system becomes more difficult to manage. There are added costs of more frequent ramping up and down of thermal power plants resources, and more frequent stopping and starting of fast-responding, peak-load facilities. In general, fossil-fuel power plants operate below their efficient operating range, leading not only to higher costs but also to greater emissions of CO_2 per MW h. Actual costs depend on the extant generating mix, as shown in Table 3.

One argument for addressing intermittency and storage 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 area 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, for example, 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. Connecting all countries of Europe together, or more generally, all wind farms that are scattered across a landscape, with many sites located offshore and in remote regions, new transmission lines will be required. If the incremental transmission cost is accounted for, the cost of wind power would be much higher than calculated in many studies. Unfortunately, studies indicate that this does not avoid the problems mentioned above, including the possibility that no wind power is available anywhere.

Table 3
Costs of reducing CO_2 emissions.
Source: Adapted from van Kooten (2010).

Generation Mix[a]	Per tCO_2 Wind penetration 10%	30%	Increase in per MW h costs 10%	30%
High hydro (60-12-18-10)	$2,467	$3,859	73%	245%
Typical (8.4-22-50-21.6)	$124	$166	26%	88%
Fossil fuel (10-0-50-40)	$44	$49	16%	58%

[a] Values in parentheses refer to the percentages of hydro, nuclear, coal and gas capacity, respectively.

Oswald et al. (2008) demonstrate that large weather systems can influence the British Isles and the European continent simultaneously. They point out that at 18:00 h 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. Likewise, Miskelly (2012) examined 2010 wind output data for eastern Australia, a large area. Based on an unusually low standard of 2% of installed capacity for the minimum acceptable level (MAL) of output and power output over 5-min intervals, the combined output of all wind farms in the region failed to produce 2% of installed capacity 109 times, the longest of which was 70 min. One typical wind farm failed to achieve 2% or more of capacity 559 times in the six months of the study, with the longest drought in output lasting 2.8 days. Not only does the entire fleet fail frequently, but also it fails throughout the year. Miskelly concludes that wind cannot be used as base-load power, and that back-up reserves must be at least 80% of installed wind farm capacity. In eastern Australia, open cycle gas turbines are needed for backup, which far less efficient than closed cycle gas turbines, but CCGT systems cannot react sufficiently quickly to variation of wind power output. Further, the open cycle turbines must be operating constantly on stand-by mode, wasting energy when the electricity is not needed. It is unlikely, therefore, that even a super grid with many wind farms scattered over a large landscape can avoid the problems and added costs associated with intermittency.

These results suggest that one should not be overly optimistic about the chances that large-scale wind developments will overcome society's need for fossil fuels. But this observation should not be used to sound the death knell for wind. As indicated in Table 3, wind power can reduce CO_2 emissions at reasonable cost for electricity grids with large fossil-fuel generating assets. Further, using wind data from Ethiopia, van Kooten and Wong (2010) found that, because the national grid was unreliable and back-up diesel generation expensive, a small community or factory could save millions of dollars per month using wind power; in this case, power from the grid (if available) or diesel sources backstopped intermittent wind, with diesel the ultimate backup. The challenge of integrating wind energy into existing electricity grids depends on so many factors that it is impossible to generalize regarding the indirect costs of wind power. The extant generation mix, the availability of suitable sites for wind farms, the availability of storage (mostly hydro assets), relative fuel prices, nearby transmission infrastructure, attitudes toward nuclear power, real and perceived externalities of various energy systems, political lobbying, and government policies regarding all of these factors and others (including the macroeconomic climate) are some of the factors that determine the economic feasibility of wind power.

Even though comparisons of the full cost of various electricity generation technologies are not available, the existing literature calls for policy intervention, mainly to address the indirect costs of wind power. Moreover, societies in the industrialized countries appear to value wind energy more than the same energy produced from other sources. For example, Borchers et al. (2007) show that customers in New Castle County, Delaware exhibit a marginal willingness to pay of 1.3 cents/kW h for wind energy because they gain more utility from wind energy as compared to fossil fuel based generation. In addition, as a renewable source of energy, wind power could be part of the solution to the energy security problem the world could face in the long run. Because these values are inadequately reflected in energy markets, governments have responded positively by providing various incentives to generate more power from wind turbines.

3.3. Externality costs

All energy systems have externality or spillover costs associated with them. The values in Fig. 1 only include financial costs to an investor; they do not correct for government subsidies, fail to take into account indirect costs on the grid, and do not take into account externality costs. Wind turbines have some externality costs related to noise pollution, visual dis-amenities and adverse impacts on wildlife, such as losses of birds and bats.[8] However, these external costs are likely to be very small compared to that of fossil and biomass fuels. Sundqvist (2004), for example, estimates that wind power causes an external costs of 0.32 cents/kW h (1998 price) compared to 11.6 cents/kW h, 8.3 cents/kW h, 3.8 cents/kW h and 2.9 cents/kW h caused by oil, coal, gas and biomass. Owen (2004) and Roth and Ambs (2004) argue that wind power could compete with fossil fuels if environmental externalities from fossil fuels are appropriately accounted for in calculating true social costs. van Kooten and Wong (2010) find wind power more attractive than biomass if impacts of their emissions on human health are accounted for. Since wind power has smaller external costs compared to fossil fuels and biomass, it would cause net external benefits when it replaces the latter. For example, the net external benefits of wind power in Sundqvist (2004), cited above, would be 11.28 cents/kW h if it replaces oil fired power generation. Similarly, the net external benefits of wind power would be 7.98 cents/kW h, 3.48 cents/kW h and 2.58 cents/kW h if wind power replaces, respectively, coal, natural gas and biomass fired power generation.

Existing studies also elucidate human health benefits of wind power. The benefits come mainly from reduction of air pollution through the replacement of fossil fuel based electricity with wind power. While estimating a variety of health related costs of coal in the United States, including the impact of air pollutants from coal combustion on public health, deaths during extraction and transport of coal from the mine to the power plant and excess cardiovascular disease from mercury emissions, Epstein et al. (2011) comes to figures ranging between 83 US$/MW h and 158 US$/MW h. If wind power replaces coal fired power generation most of this cost could be attributed to wind power as its health benefits. Similarly, Gale and Lax (2013) estimates costs of air pollution 187.5 US$/MW h for coal, 135 US$/MW h for oil and 22.5 US$/MW h for natural gas. These could be attributed to wind power as external benefits if wind power replaces power generation burning those fuels. Estimating health benefits of two wind farms in the United States (580 MW at Altamont Pass, California and 22 MW at Sawtooth, Idaho) compared to the cleanest fossil fuel, natural gas, McCubbin and Sovacool (2013) find that the human health and climate benefits of wind power would range between 1.5 cents/kW h and 11.8 cents/kW h. Thus, wind power produces net external benefits if it replaces power generation burning fossil and biomass fuels.

Table 4
Key data to analyze the externality costs associated to the release of CO_2.

Technology	Carbon content of the fuel ($kgCO_2/GJ$)		Heat rate (Btu/kW h) or thermal efficiency (%)	Source
Gas CC	56.1	Min	58%	NEA/IEA
		Max	55%	NEA/IEA
IGCC w CCS	29.5*	Min	37%	NEA/IEA
		Max	10,520 Btu/kW h	Lazard
Supercritical coal	98.3	Min	46%	NEA/IEA
		Max	12,000 Btu/kW h	Lazard

* Assuming that CCS reduces carbon emissions by 70%.

In the case of climate change mitigation benefits of wind power, we have incorporated the costs of CO_2 emissions in analyzing various fossil fuel technologies against wind for generating electricity. We first explore how the levelized costs of electricity generation are affected by the inclusion of the externality cost imposed by CO_2 emissions (damages due to local air pollution are not included due to a lack of data). Some measures of the thermal efficiency of a plant and of the carbon content of the various fossil fuels are needed in order to perform an evaluation of the carbon dioxide externality cost of generating power from various technologies. Key data used in this study are summarized in Table 4.

Given the complexity of the task, we simply employ a sensitivity analysis by considering carbon costs ranging from $0/tCO_2$ to $100/tCO_2$. The levelized costs of various technologies are plotted in Fig. 3 against the climate damage. The figure demonstrates that onshore wind power starts to become comparatively cheaper than carbon intensive technologies if a carbon penalty of $20/tCO_2$ is imposed on all generation technologies.[9] It is also clear from the figure that the minimum levelized cost of offshore wind exceeds the maximum value of the levelized cost of the vast majority of the fossil fuel technologies, even for a carbon price of $100/tCO_2$—offshore wind generation is currently unattractive compared to power generation from fossil fuel. Climate change mitigation is consequently insufficient in itself to justify investment in offshore wind energy.

An alternative interesting comparison pits wind against nuclear power. In a study of Ontario's power system, Fox (2011) used the screening curve approach to find the optimal generation mix from the load duration curve, the energy options available (e.g., hydro potential, coal and gas deposits, wind sites), and the carbon tax.[10] Nuclear power bested wind as the tax rose because wind could not be relied upon for base-load capacity, the capacity factor for wind farms was too low, and too much additional reserve capacity was needed relative to nuclear power. Coal was not included in the generation mix although gas and hydro power were chosen.

[8] Some studies such as Erickson et al. (2005) argues that the number of bird and bat fatalities due to wind turbine collisions is actually very small compared to deaths due to collisions with buildings, towers, vehicles, power lines and other structures.

[9] This is very different compared to solar, where the minimum values of levelized costs of solar energy technologies would be higher than the maximum values of the levelized costs of fossil fuel technologies even if the climate change damage costs of 100/tCO2 are imputed to fossil fuel technologies (see Timilsina et al. 2012).

[10] For a discussion of load duration and screening curves, see van Kooten (2013a, pp.410–414).

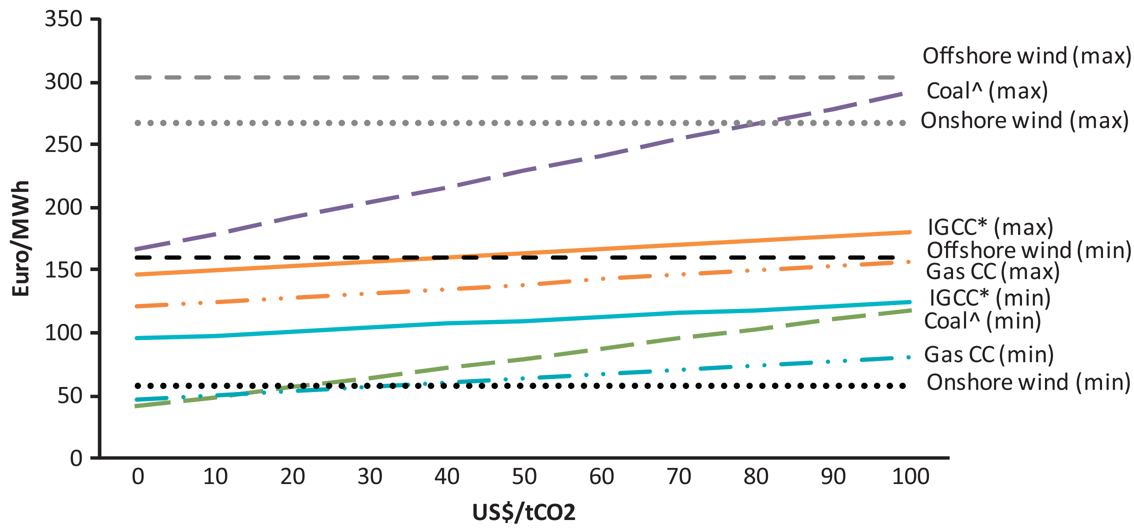

Fig. 3. Economic attractiveness of wind power when the cost of carbon is accounted for. *Note*: Basic data was adapted from NEA/IEA, 2010 and Lazard (2011). ^ Supercritical coal, * IGCC with CCS

A similar result was obtained by van Kooten et al. (2013) for the Alberta system. In contrast to Fox, these authors began with the extant generation mix (which included 350 wind turbines with a rated capacity of 805 MW). In 2010, the Alberta load averaged 8188 MW, with peak load equal to 10,227 MW and minimum (or base) load of 6524 MW. A unique feature of the Alberta grid was a 650 MW transmission intertie into British Columbia's hydroelectric system, which could store intermittent wind power. Indeed, prior to Alberta's investment in wind power capacity, the intertie was used to level output from Alberta's base-load coal plants—to keep the coal plants from ramping up and down too rapidly. British Columbia would purchase low-priced electricity at night when demand in Alberta was low, selling hydropower to Alberta during peak daytime hours. The authors imposed a cost for removing assets and an annualized fixed cost of adding new capacity that varied by generation type. A mathematical programming model was used to determine the optimal allocation of the 2010 load among generating assets, with wind treated as must run as based on actual 2010 output. When no nuclear power was allowed in the mix, it was optimal to invest in new wind resources once the carbon tax reached \$50/tCO_2, although coal assets were not shed until the price reached \$75/tCO_2. However, even when the tax reached \$150/tCO_2, one-third of the original coal-fired capacity was retained for base load purposes, despite the installation of 19,750 MW of wind capacity. Further, along with the added wind capacity came a 20% increase in gas plant generating capacity.

When nuclear power was permitted into the generation mix, it began to enter at \$25/tCO_2; by the time the carbon price reached \$75/tCO_2, all coal assets had been shed, and gas plant capacity had been halved (while initial wind capacity remained unchanged). The reason why nuclear was able to out-compete wind was due to the usual factors, but most importantly it was due to the high cost of gas plant capacity that accompanied wind and was unnecessary in the case of nuclear power. Further, the ability to store unneeded power at any given time via the Alberta-BC intertie facilitated operation of nuclear capacity beyond base load—nuclear power outbid wind in the use of this storage asset.

4. Policy instruments to support wind energy

Many countries have developed strategies to encourage wind power development to address their commitments to control CO_2 emissions. As of early 2012, at least 118 countries had renewable energy targets including developing countries such as Brazil, China, the Dominican Republic, Egypt, India, Lebanon, Rwanda, South Africa, and Thailand (REN21, 2012).[11] The targets vary significantly across countries. Scotland, Denmark and Germany have set 2020 targets to supply 100%, 50% and 35%, respectively, of their total electricity demand through renewable sources (REN21, 2012). Other countries have targets varying between 2% and 50%, but over a period that might extend to 2030. Comparing countries' progress in terms of their intermediary renewable energy targets show that some clearly exceeds their target (Bulgaria, Poland, Sweden), whereas others fall short of their intermediate goals (France, Greece, Portugal) (EWEA, 2013).The main policy instruments countries employ include feed-in tariffs (FITs), capital subsidies, tax incentives, tradable energy certificates, mandatory targets, renewable energy portfolio standards, priority in dispatching and guarantee to access transmission lines, and long-term contracts. Among these policy instruments, FITs that oblige electricity utilities to buy electricity generated from renewable sources at above-market rates are the most common. In a pure FIT system, producers get a fixed price per unit of electricity fed onto the grid for a specified period of 5 to 20 years. FITs are a type of price-based policy instrument, because prices are fixed in advance, but the final quantity of renewable energy obtained under such system is uncertain (Menanteau et al., 2003). This type of policy instrument is favored by investors as future prices are known in advance, therefore suppressing a category of risks. In that sense, FITs are effective and result in the quick installation of renewable energy capacity, provided that the FITs are sufficient. As of mid 2012, most developed and some developing countries introduced FITs for wind energy. However, FITs have the drawback of being immune to fluctuations in electricity demand and/or electricity spot market prices (Ragwitz et al., 2012). Consequently, more and more countries, including Germany, Denmark, Slovakia, Finland and the United-Kingdom, are moving into specialized forms of FIT such as: fixed premium, feed-in premium with cap and floor prices and sliding premium (Ragwitz et al., 2012), in order to increase the effectiveness and efficiency of support systems put in place to support wind power development.

[11] Countries normally have targets for renewable energy as a whole, aiming to promote all possible sources of renewable energy instead of favoring a particular one. The policy instruments are, in general, common to all renewable energy sources.

The Canadian province of Ontario has, arguably, the most lucrative FIT scheme in the world. An on-shore wind farm receives 11.5 ¢/kW h and, what is more important is that 20% of the FIT is indexed to inflation for a period of 20-years.[12] This contrasts with the approach in Alberta where the wholesale market is deregulated and where there are no subsidies (and wind generating capacity has expanded rapidly) and British Columbia where long-term contracts are employed (and much less wind power has come on stream). In India, the majority of the states have started a feed-in tariffs scheme to support wind energy.

Direct subsidies and tax credits are also common instrument used by policymakers. Most developed countries and some developing countries have provisions to provide capital subsidies (on investment and/or operation) or other forms of aid to renewable energy producers. In the United States, for example, a wind energy production tax credit (PTC) is used to encourage investment in wind generating capacity. It provides an income tax credit of 2.2 ¢/kW h that is adjusted annually for inflation and is valid for the first 10 years of production, but it applies only to large-scale power installations, while the existence of the program is subject to the whims of Congress. Since 1992, the Congress let the PTC for wind expire four times before eventually extending it again, giving birth to a boom and bust cycle in the installation of new wind power capacity.

Australia, Japan, California and some European countries have introduced tradable Renewable Energy Certificates (tRECs), also known in Europe as Tradable Green Certificates (TGC) to promote all forms of renewable energy. Under such a system, power companies are required to meet a given renewable energy target (in terms of installed capacity or share of electricity sold). Power companies will either be able to build new capacity or buy tRECS on the secondary market to meet their renewable energy targets. TRECs instruments are quantity-based policy instruments in the sense that the final quantity of renewable energy is known in advance, whereas the final cost to get there is uncertain (Menanteau et al., 2003). This type of policy instrument is deemed more efficient than FITs because the cheapest renewable energy technology and the best locations will be developed first. Another advantage of such certificates is that renewable power does not necessarily have to be delivered, thereby avoiding transmission constraints. For example, a jurisdiction that generated wind or hydro power can sell tRECs to another jurisdiction, thereby incurring an increase in associated CO_2 emissions. This works well if both jurisdictions have targets to reduce CO_2, but could potentially be open to corruption as well. Nonetheless, by buying these certificates, consumers could help increase production of green power irrespective of the production location (USEPA, 2008).

The selection of policy instruments is highly influenced by national situations. Most countries have introduced more than one policy instrument. The small contribution of wind power to the global electricity supply mix implies that existing policies are not sufficient or existing fiscal incentives are too small. 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 supported by its potential. With the exception of carbon offset payments under the CDM, wind power does not receive 'green' benefits, while fossil fuels are not taxed for their environmental externalities. Without policy intervention to establish a level playing field, wind power may not be able to compete with fossil fuel based electricity generation technologies.

[12] For a discussion of global FIT programs and a cost-benefit analysis of the Ontario program, see van Kooten (2013b).

5. Wind power and international climate change initiatives

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

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 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; the various Canadian territories have set ambitious goal including the installation of 4.6 GW of new wind capacity by 2020 in Ontario and 1.2 GW of wind capacity in the Maritime Provinces by 2015 and Spain is planning to reach 35 GW of wind capacity, including 3 GW of offshore wind by 2020. Developing countries are now starting to set targets for developing wind power too. For instance, Egypt is planning to have 7.2 GW of wind power capacity operational by 2020 and India set the target of 15 GW of added wind capacity between 2012 and 2017. In developing countries, the Clean Development Mechanism (CDM) has played an instrumental role in implementing wind power projects. By mid-2013, 2609 wind power projects with a combined capacity of 120 GW were registered under the CDM (URC, 2013a). While these projects are distributed across the globe, nearly 90% of the total projects with about 81% of the total capacity are concentrated in China and India. China alone accounts for 70% of the total installed capacity. Wind power projects account for approximately 29% of the total CDM projects already registered or in the pipeline. In terms of GHG mitigation, these projects share 19% of annual certified emission reductions. In addition to CDM projects, 50 wind energy projects have been already registered or are in the process of registration in economies in transition by mid-2013 under Kyoto's joint implementation mechanism (URC, 2013b).

6. 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. The global wind power generation capacity expanded rapidly from only 10 MW in 1980 to 282 GW by the end of 2012, with an average annual growth rate of about 27%. This growth is 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, wind power still accounted for only 2–3% of the global electricity supply as of 2012. 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 5% to 13% of the global electricity supply by 2035, and that the earth's wind resources are theoretically sufficient to cover the global energy needs. The ability to continue expansion of wind power will depend, however, on the specific circumstances a country or a region is facing, 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 the price of fossil fuels, economic and political developments surrounding nuclear power, and the cost and availability of other renewable sources of energy.

Based on publicly available data from various sources, our analysis shows that the economics of wind power varies widely across countries and locations. Wind power is still expensive as compared to most traditional technologies to generate electricity. However, introduction of externalities costs to fossil fuels significantly help wind power's competitiveness. For example, a climate change damage cost of US\$20/tCO_2 imposed to fossil fuels would make onshore wind increasingly competitive to all fossil fuel for power generation. However, this does not happen to offshore wind even if the damage cost is increased to US\$100/tCO_2.

Wind power faces higher costs due to a large number of technical, financial, institutional, market and other constraints. While the intermittent nature of wind power raises indirect costs, the relative remoteness of locations where wind resources normally exist increases capital costs. In addition, the relatively higher upfront capital cost and lack of access to financing, especially in developing countries, pose further constraints. To support wind power development, many countries have introduced a variety of policy instruments, the most common of which are feed-in tariffs, capital subsidies, tax incentives and tradable certificates. However, existing policy instruments alone are not adequate to increase significantly the share of wind power in the global electricity supply mix. Hence, new and innovative policy instruments and strong institutional support are necessary.

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 May 2013, wind power projects with a combined capacity of more than 120 GW had already been registered under the CDM. Moreover, more stringent GHG mitigation targets in the future will likely help accelerate the expansion of wind power across the globe.

The existing policies and the climate change initiatives have substantially boosted deployment of wind power. The continued decrease in wind power costs would also help it become more competitive in future. However, the major obstacle of wind power is the intermittent nature of wind resources. This technical constraint would pose the biggest challenge to the future development of wind power.

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