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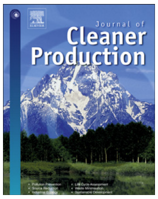

Mismatch of wind power capacity and generation: causing factors, GHG emissions and potential policy responses

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ABSTRACT

Policies to assure combatting climate change and realising energy security have stimulated a rapid growth in global installed capacity of renewable energy generation. The expansion of power generation from renewables, though, has so far lagged behind the growth in generation capacity. This indicates missed and relatively cheap opportunities to reduce GHG emissions. This paper sheds light on the mismatch between installed capacity and power generation for the case of wind power. It analyses and compares wind power developments in the four countries that contributed most to the increase in wind power capacity during the last decade: namely, China, the United States, Germany and Spain. We estimate the dynamics of capacity utilisation of wind power installations and identify its drivers. Finally, we identify potential policies to reduce the gap between power capacity and generation, which will contribute to cost-effective reduction of GHG emissions.

1. Introduction

A transition of renewable energy is crucial for making our economies environmentally sustainable. With adequate policy support, renewable energy sources have the potential to meet up to 80% of the world's energy supply by 2050 (IPCC, 2012). In the last decade, renewable energy has experienced a very high rate of expansion. Between 2004 and 2013, power generation capacity of renewables[1] grew by more than 600%, from 85 GW to 560 GW (REN21, 2014). Renewable energy sources have recently surpassed fossil fuels in terms of global capacity additions and investment per year.[2] Nevertheless, the renewables share of total primary energy supply has increased only 0.4% from 2006, when its share was 10.6%, to 11% in 2013 (IEA, 2014b). Most discussions of this rather disappointing development focus on stimulating further diffusion and associated investment in capacity. Nevertheless, the increase of power generation from renewables has traditionally lagged behind the expansion of capacity installation.

Largely due to policy support in the form of subsidies or green certificate systems, renewable energy sources have shown high expansion rates of installations. However, at the same time, there is a serious mismatch betwee2n installed capacity and actual power generation of renewable energy. This is a somewhat overlooked issue in the literature, which is surprising as it suggests a missed opportunity to contribute effectively and relatively cheaply (cost-effectively) to a reduction in GHG emissions.

The mismatch applies particularly to electricity generation from wind power. Wind power has the largest installed capacity among the intermittent renewable energy sources with 318 GW by 2013 (REN21, 2014). Between 2000 and 2012, its globally installed capacity has grown at an average rate of 24% per year (IEA, 2014). In contrast, electricity generation from wind started to rise only from 2008 on, at an average 0.3% per year, resulting in a share of 2% of global electricity production in 2012 (IPCC, 2014). Yet, if all generation capacity then installed had been used, wind power could have

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[1] The data presented hereafter on renewable energy exclude hydropower since the focus is on intermittent renewable energy sources.

[2] In 2013, renewables contribute 58% to total global (net) capacity added. For the third consecutive year renewables surpassed fossil fuels and nuclear in terms of investment in new power-generation capacity, comprising US$ 214.4 billion – almost double the net investment in fossil-fuel power, namely US$ 148 billion. This excludes replacement of electricity plants (BNEF, 2014; IRENA, 2014).

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supplied 14.7%[3] of the global electricity consumption in 2012. At the same time, in 2013 alone, an estimated 212 GWh of electricity generated by the existing capacity of wind power were not transmitted to the grid (Li et al., 2015). This is partly explained by the falling prices of coal and gas, but also by low capacity factors[4] and barriers to integration with the broader energy system (Baritaud, 2012; IEA, 2014d; Volk, 2013). So the past decades of policy support have led to extensive deployment of wind power but its capacity of electricity generation has remained under-exploited.

This paper analyses electricity generation from wind power[5] in order to shed light on the mismatch between installed capacity and power generation. In addition, it qualitatively evaluates the consequences for GHG emissions. The study focuses on the four countries with the largest wind power installations in the past decade, namely China, the United States, Germany and Spain. The main contributions of this paper are three: mapping the main drivers of wind power capacity utilisation within the current energetic system; assessing foregone opportunities in terms of GHG emissions reduction; and identifying potential policies to narrow the gap between electricity capacity and generation from wind power.

The remainder of this paper is organised as follows. Section 2 reviews the factors determining electricity generation from wind power within the current system. Section 3 estimates wind power capacity utilisation in the four countries studied, identifies drivers of the gap between capacity and generation, and explains differences found among countries. This is followed in Section 4 by a discussion of foregone opportunities to reduce GHG emissions, and policies to improve wind power generation with given capacity. Section 5 concludes.

2. Wind power: driving forces of capacity utilisation

In this section we examine the main features of electricity generation from wind power followed by discussion of the determinants of its capacity utilisation.

2.1. Electricity generation from wind power

Wind power systems produce electricity by harnessing the kinetic energy of wind and converting it into electric energy. For electricity generation, the dominant design of wind power systems is the utility-scale, the so-called “wind farms”. Normally built in geographical areas characterised by consistent wind flows, wind farms combine several wind turbines with a balance of system of electrical components (such as transformers and grid interconnectors). Each wind farm has a peculiar dynamics that defines its power generation capacity. This dynamics is based on several features, such as the wind farm's capacity factor and connectivity to the power grid.[6] Electricity generated by wind farms is introduced into electric grids by transmission system operators (TSOs) and delivered to consumers by distribution system operators (DSOs).[7] Since electricity cannot be stored cost-effectively in large quantities, supply and demand must be balanced in real time at all times. This task is normally performed by a grid management system that coordinates TSOs and DSOs. Because electricity networks are highly interconnected, any imbalance between supply and demand in one location may affect the entire network. Hence, electricity provision to consumers depends on the system operators' capacity to guarantee that supply evens demand across the whole network at all times. To this end, a platform is used to allow all electricity producers to communicate in real time with the system operator. In a competitive electricity market, this central platform works also as a bidding market, where the cheapest offers can be identified and dispatched.

Electricity networks are complex systems, with many complementary components and feedbacks. Moreover, each location and each market have different energy mixes, network structures, levels of wind penetration, etc. Here we focus on the current electricity system to analyse the factors considered determinant of the capacity utilisation of wind power installations. Instead of looking at the conditions enabling a future all-renewables system, we recognise fossil fuels as a complementary energy source, and acknowledge the need for redundant capacity of wind power upon this current hybrid system. The following sections briefly review the main determinants of capacity utilisation of wind power installations, namely: capacity factors, system flexibility, and market integration.

2.2. Capacity factor

The capacity factor is an indicator of electricity-generating capacity that specifies the percentage of time that a wind farm produces electricity during a representative year. It is calculated as the ratio of average power delivered in a given period compared to the theoretical maximum power, for a single turbine, a wind farm (covering several turbines) or an entire country (with several wind farms). Capacity factors vary following location and the design of wind turbine and wind farms. The local wind resource is considered the most important factor affecting the performance of wind energy systems (Blanco, 2009). Location influences the capacity factor due to wind conditions. These are rated by capacity of kinetic energy generation (derived from the weather conditions), but also by transmission enabling factors, such as: correlation with peak demand; proximity to end-consumers; and variability and predictability of wind blow (Baritaud, 2012; IEA, 2014d).

Design of wind turbines influences the capacity factor by nameplate capacity (maximum power generation capacity) and suitability to the wind regime. Recently, turbine design has evolved towards higher power capacities by increasing the height of the tower and the length of the blades (IEA, 2014c). On average, however, the average height and rotor diameter of turbines has grown more rapidly than average power capacity. This decrease in the specific power, or ratio of capacity over area, has pushed up capacity factors for the same wind speeds (Wiser and Bolinger, 2013). For lower wind speeds, rotors with high masts and long blades in relation to generator size are the most suitable, and sometimes present even higher capacity factors than high speed designs (Bortolini et al., 2014). Moreover, because lower-wind-speed areas are often closer to consumers than the best wind locations, this offers additional advantages as lower transmission losses and higher flexibility of dispatch. While several designs are in use today, new grid-connected turbines had an average size of 1.8 MW in 2012, up from 1.6 MW in 2008 (Navigant, 2013). The largest commercial wind turbine currently available is 7.5 MW, whereas turbines with a rated capacity between 1.5 MW and 2.5 MW respond for the largest market share

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[3] Full capacity refers to maximum power output. The calculation is based on 1625 Mtoe of electricity consumption (IEA, 2014b) and 318 GW of installed capacity (REN21, 2014).

[4] The term “capacity factor” denotes the ratio of average power delivered in a given period compared to the theoretically maximum power that can be generated (further details are provided in Section 2.2).

[5] The analysis is focused on electricity generation from onshore and grid connected wind power installations because this setup is the most widely deployed. Offshore wind power is mentioned whenever relevant for the discussion.

[6] For a comprehensive discussion on wind farms see Chowdhury et al. (2013) and Herbert et al. (2014).

[7] The focus on transmission and/or distribution operators, rather than on vertically integrated utility structure, is given by the fact that these play key roles in markets with significant shares of wind power generation.

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Table 1
Capacity factors for different wind turbine designs.

Onshore turbine nameplate capacity	Capacity factor projected	Standard deviation
<100 kW	18%	75.4%
100 kW–1 MW	22%	75.1%
>1 MW	31%	77.5%

Source: Arvesen and Hertwich, 2012.

(IRENA, 2012). Onshore wind has a capacity factor ranging from 20% to 40% (IPCC, 2012), depending on the turbine design (see Table 1).

In the last decade, the expansion of wind power installations generated information about realised capacity factors that were in general lower than the originally assumed ones, namely with an order of magnitude of 35% (Arvesen and Hertwich, 2012). This has significant consequences for investors since the average capacity factor over the 20 years lifetime of a turbine defines the electricity produced and, hence, the return on investment. For example, for the EU15, the average capacity factor realised in 2003–2007 was 21%, rather than the initial projected 35%. This resulted in a 66% increase[8] of average levelized cost of wind power generation (Boccard, 2009). Even though oscillations across time and regions make capacity factors difficult to forecast precisely, the industry has now assembled experiences in highly diverse contexts, which offer relevant information to improve the decision about future installations, as well as to better forecast electricity production from current installations.

2.3. *System flexibility*

Competitive operating costs or merit-order effects make electricity from wind to have priority of being dispatched into the grid, thereby displacing the use of other electricity sources (Jónsson et al., 2010; Pereira et al., 2014). This results in electric system operators and markets using other generators to meet demand minus any available wind energy. Larger shares of intermittent wind-generated electricity lead to higher variability in the electric system.

Due to this higher variability, further integration of intermittent renewable energy, as wind, requires additional flexibility of a network, i.e. increased capacity to receive variable and uncertain power flows. The impact of intermittency of renewable energy sources usually becomes noticeable beyond 2–3% of total electricity generated, but is expected to create technical or cost barriers to integration only with penetration levels above 20% (GEA, 2012). Several countries (e.g. Denmark, Germany and Spain) have electric systems expected to support intermittent power inputs at annual shares between 25% and 40% of total electricity supply (IEA, 2014d).

Without additional flexibility, a system is unable to absorb increasing shares of wind-generated electricity, leading to higher curtailment[9] rates. In this case, the capacity utilisation of a wind farm would be maintained at levels below what the wind regime enables, rather constrained by the grid capability. This is of major concern since it limits the capacity of a wind farm to achieve, or increase, net energy generation. This results in a lower rate of return on investment and less GHG emissions being reduced.

To improve network flexibility, the main approaches currently used in the electricity sector involve changes in four areas, namely network infrastructure and management, portfolio diversity, storage and demand side management. These are briefly discussed.

2.3.1. *Network infrastructure and management*

Network infrastructure can be strengthened by reinforcing the physical structure and extension of transmission and distribution lines. This allows the system to support wider and sudden power input variations, as well as to connect with more distant power generation and consumption centres (Benatia et al., 2013). Grid management can enhance flexibility essentially by improving the accuracy of wind forecasts and by reducing response and communication times between generators and system operators (Denholm and Hand, 2011; Li et al., 2015).

An additional mechanism to increase a network capacity to absorb wind power is to dynamically regulate transmission capacity with relation to wind and temperature. This technique is known as “dynamic line rating” (DLR). For example, a wind of 1 m/s can increase line rating as much as 44% due to the cooling effect of wind on the transmission lines (IEA, 2014d). Further benefits from applying DLR are reduced congestion and re-dispatch operations (Cochran et al., 2012).

2.3.2. *Portfolio diversity*

Portfolio diversity refers to the geographical expansion of wind farms and grid infrastructure, as well as to complementary and non-intermittent energy sources, known as dispatchable plants. The first type of diversity offers two advantages: enhanced demand–supply balance as within larger geographic areas variations of supply by individual wind farms tend to cancel out (Neuhoff et al., 2013); and higher forecast accuracy for the electrical system since geographical dispersion reduces the impact of forecasting errors associated with individual wind farms (Albadi and El-Saadany, 2010). Dispatchable plants increase a system capability to cope with variability of wind-generated electricity either by attending peak demand or by guaranteeing minimum supply. Here, the most suitable electricity sources are hydro and gas-fired plants due to their fast ramp up (Jacobson and Delucchi, 2011).

2.3.3. *Energy storage*[10]

Storage technologies have the potential to increase network flexibility required for wind-generated electricity. Because storage functions as both an electricity producer and consumer it can smooth electricity flows, absorbing power during peak generation and returning it to the grid during peak demand (Zhao et al., 2014). Through this mechanism of quick adaption to intermittence, it offers additional advantages such as: increased reliability by neutralising forecast errors; and lower network requirements in function of reduced stress over transmission and distribution lines and operators (Luo et al., 2014).

Unfortunately, all storage technologies currently available have considerably higher costs compared to other flexibility options. Storage has a cost of about US$ 1200/kW for typical projects (IEA, 2014d). By 2010, electricity storage capacity amounted to 125 GW worldwide, corresponding to about 3% of global electricity generation capacity (Roberts and Harrison, 2011). To date, pumped hydroelectric (pumped hydro) is the most mature and cost-competitive storage option. It accounts for 99% of installed

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[8] Levelized cost is the ratio of fixed cost to capacity factor. In this case, the ratio of projected to realised capacity factor is 35/21 = 1.66, so that the cost is 66% above the initial estimate.

[9] Curtailment refers to reductions of power dispatch into the grid in response to a transmission capacity shortage, with the aim to secure system reliability.

[10] Storage refers to technologies that absorb electricity at a given time and return it at a later date. Technologies based on seasonal storage capability (days or weeks), such as hydrogen storage and power to gas, are not considered here because they are still in a very early stage of development.

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Table 2
Renewable power capacity: top countries in 2013.

Technology	Power generation capacity in GW				
	World	China	US	Germany	Spain
Bio-power	88	6.2	15.8	8.1	1
Geothermal power	12	0	3.4	0	0
Hydropower	1000	260	78	5.6	17.1
Solar PV	139	19.9	12.1	36	5.6
Concentrating thermal solar power (CSP)	3.4	0	0.9	0	2.3
Wind power	318	91	61	34	23
Total renewable power capacity	1560	377	171	84	49

Source: REN21 (2014, p. 106).

capacity by 2012, with Japan (23 GW) and EU-15 (13 GW) as the main markets (IEA, 2014d). Furthermore, recent studies indicate that storage can become cost-effective only within specific technology mixes and with wind-generated electricity responding for at least 48–51% of the total (Tuohy and O'Malley, 2011).

2.3.4. *Demand side management*

Demand side management (DSM) refers to a mix of measures to improve flexibility by controlling consumption. The main objective is to change a system or utility's load shape, reducing or avoiding peak demand and peak generation. An incentive is often offered to customers in return for participation. Programmes focus on customers' voluntary responses, mainly by setting smart energy prices that incentivise targeted consumption behaviour (Finn and Fitzpatrick, 2014). The overarching goal is to assure that prices reflect real-time availability of electricity, thereby providing the adequate incentives to drive consumers' behaviour (Clastres, 2011). DSM is considered one of the most promising low cost instruments for additional flexibility. It enables short-term redistribution of electricity demand without many additional infrastructure requirements (Yang et al., 2014).

2.4. *Market integration*

Integration of wind power in electricity markets is still evolving and shows variation across countries. So far, wind-generated electricity has been remunerated by support schemes at the margin of competitive electricity markets. Further market integration depends on a system capable of securing reliability and security of supply at least cost while using the largest amount of wind-generated electricity possible. Because of intermittency and lack of storage options, increasing the volume of wind-generated electricity challenges the system to balance generation and consumption at all times. This requires synchronous coordination between power generators, system operators, and consumers. The use of market-based solutions, such as price signals, to push for timely and efficient responses, is here complemented by technologies that shorten communication and response times and increase control over power flows (IEA, 2014d). Market integration has been promoted by a number of instruments. Below, we discuss the most widely employed ones.

2.4.1. *Balance of dispatch*

The maintenance of electricity supply depends on the balance of dispatch among all generators, of wind power and all other energy sources present in a system. Trade integration among dispersed wind power generators and use of complementary and non-variable sources (e.g. hydro or gas-fired power plants) have proved to be the most cost-effective solutions so far (Baritaud, 2012; Jacobson and Delucchi, 2011; Volk, 2013). Due to variability and uncertainty characteristics of wind power, short-term bidding is considered more suitable than the current pattern of long-term contracts (Neuhoff, 2011; Rubin and Babcock, 2013). The closer to generation time a purchase contract is arranged the more accurate in terms of the amount and timing of wind power generation it tends to be. With higher accuracy, larger amounts of wind power can be dispatched to the grid without reducing security of supply or increasing system costs (Wang, 2014). This also entails further benefits by reducing the need of reserve capacity as well as curtailment risks.

At the same time, because a higher penetration of wind electricity tends to lower electricity prices (Ketterer, 2014; Twomey and Neuhoff, 2010), conventional electricity generators may become uneconomic over time. However, these non-intermittent plants are necessary to guarantee system supply in situations of too little or too strong wind. Hence, there is a need to provide incentives to maintain a safe level of conventional power generation. So-called markets for ancillary services,[11] where remuneration is based on tasks other than power effectively delivered, are an option. In this case, conventional power generators could be rewarded by capacity available and operation capabilities such as fast ramping, ramp rate control, quick-start, low turn down, and inertial response (Cochran et al., 2012).

2.4.2. *Reduced time of response*

Reducing the time intervals of system operation better reflects wind power generation. Dynamic markets that function on intervals of minutes, rather than hours, are more suitable for integrating wind power because they allow to better track actual generation and net load, without the need to rely on reserves (Clastres, 2011). Furthermore, dispatching in shorter intervals enhances coordination among different wind farms, and with conventional generators, improving overall system efficiency (IEA, 2014d). Currently, the best practice dispatch interval is 5 min – namely, at ERCOT[12] in Texas, US (Zarnikau et al., 2014); but 1 h tends to be the rule. Another mechanism for reducing time of response is to shorten gate closure times,[13] so that trading can happen as close as possible to real-time operations. This increases capacity use in

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[11] Ancillary services refer to operations required to warrant continuous electricity supply, such as scheduling and dispatch, reactive power and voltage control, power loss compensation, load following, power balancing and curtailment control. Historically, these services have been provided mainly by conventional power sources. With large penetration of wind, these conventional power generators may need to continue generating electricity above required levels just in order to be available to provide ancillary services (IEA, 2014d).

[12] ERCOT refers to Electric Reliability Council of Texas, the system operator responsible for the electric grid and 75 percent of the state's electricity market.

[13] Gate closure time refers to the future time at which the market commits to deliver electricity. After gate closure, it is not possible to change electricity supply or demand offers. Most markets are based on a day-ahead trading, which closes at mid-day on the day before power generation. The second most common market is the intra-day, where trading takes place on the same day as physical delivery of electricity (IEA, 2014d).

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two ways: reductions of forecast errors to a minimum; and dispatch planning closer to actual generation, which tends to be superior to figures from long-term forecasts (Wang, 2014).

2.4.3. *Local marginal pricing*

Local marginal pricing (LMP), or nodal pricing, refers to the practice where grid constraints are considered in market clearing at the local level. With LMP, demand and supply are cleared at several points in the network, so that each generator adapts its power load to the local limits of the grid (Cochran et al., 2012). In the short-run, this enables the market to be co-optimised following grid constraints. Simulations of an integrated European network using LMP found that it could promote an increase of power transfers among countries of up to 34%, depending on the level of wind penetration (Neuhoff et al., 2013). In the medium and long-run, LMP builds up accurate system information about the need, or excess, of resources in particular locations, as well as profitability (Lewis, 2010). This information about resources needs is also useful to identify and promote optimal balance between network improvements and generation costs, since it enables generators to factor future transmission costs into decisions about location (Volk, 2013).

2.4.4. *Curtailment control*

Electricity system operators have to be capable of curtailing wind-generated power. In periods of low demand, negative pricing can stimulate generators to curtail power, reducing the pressure on the grid and on average prices (Cochran et al., 2012). In periods of peak generation, curtailment can shave off output peaks reducing the need for additional infrastructure and increasing wind power overall utilisation factor (Holttinen et al., 2011). Hence, a trade-off between curtailment level and network infrastructure influences overall system performance. In general, optimal levels of curtailment are necessarily low due to the fact that power generation costs rise exponentially after a certain curtailment threshold (Burke and O'Malley, 2011).

2.4.5. *Cross-border trade*

Electricity trade between national markets helps pooling the expensive capacity resources required to maintain electricity supply and adds overall flexibility to the energy system, facilitating wind power integration in different ways. First, market integration of larger geographical extensions reduces peak demand. As a consequence, the need for balance of supply is diminished, as well as the costs related to capacity reserve and grid management services (Neuhoff, 2011). At the same time, large wind areas tend to reduce uncertainty about electricity production since forecast errors at different locations cancel each other out (Böckers and Heimeshoff, 2014). In addition, by promoting more intensive and less uncertain transmission flows, cross-border trade can enhance the value of the transmission network and reduce system operation costs (Baritaud and Volk, 2014).

3. How much electricity is generated from wind?

Wind energy is the most variable, unpredictable, and widely deployed of the intermittent renewable energy sources. Therefore any factor that negatively affects capacity utilisation of wind plants today is likely to be a constraint for other technology options, such as solar PV. Here we examine electricity generation from wind power in the four countries with the largest shares of wind power capacity installed between 2005 and 2011, namely China, the United States, Germany and Spain (Table 2). Power capacity installed has been chosen as the main criterion to select the countries studied here, for two reasons. First, market size has been recognised as a main driver of wind power development (Lewis and Wiser, 2007; Neuhoff et al., 2013). Second, there are various unresolved challenges associated with the integration of large amounts of wind-generated electricity (as discussed in Sections 2.3 and 2.4), which are especially relevant for a transition to a low-carbon system. In the next sections we present the estimation of capacity utilisation for each of the four countries studied. A discussion of possible explanations follows.

3.1. *Capacity utilisation*

Capacity utilisation refers to how much electricity is actually produced by wind power compared to installed generation capacity. Here we refer to the ratio of annual electricity output to installed capacity as “realised capacity factor” and use it as an indicator of capacity utilisation. Annual realised capacity factors are calculated for the four countries in the period 2005–2011, using data on electricity output (in GWh) and installed generation capacity (in GW) from the International Energy Statistics of EIA (2014). The analysis focuses on the period 2005–2011 because it showed the highest growth rates of wind power installations since the industry achieved maturity.

A formal expression for the realised capacity factor of a country in a year t ($RCF(t)$) is as follows:

$$RCF(t) = \frac{WEG(t)}{IGC(t) \times H}$$

Here $WEG(t)$ is the total wind electricity generation in year t (in GWh), $IGC(t)$ is the total installed generation capacity of wind power in the corresponding year (in GW), and H is the number of hours in a year, which we set equal to 8760 (i.e., 24 h times 365 days). Electricity generation and capacity data are for December 31 of each year. Installed capacity data is based on the maximum-rated output of a wind power generator.

Table 3 shows data on electricity generation from wind in the four countries studied. In spite of the diversity in terms of scale and growth rates, the *RCF* values for the four countries fall in a very narrow range. Increases in installed capacity and electricity generation contrast with the maintenance of realised capacity factors for wind under a 30% ceiling (DOE, 2010). Compared to *RCF*, *WEG and IGC* growth rates are largely superior in the period. In the U.S., where *RCF* improved the most, it rose 30%, whereas *WEG* and *IGC* increased by factors of 5 and 4, respectively. The Chinese experience shows a much wider gap with *RCF* falling by 38% while *WEG* and *IGC* growing by factors of 30 and 40, respectively. Germany and Spain had lower, reverse, *RCF* variations (+6% and −8%, respectively), and also lower expansion rates of *WEG* and *IGC* (around 60% in Germany and 100% in Spain).

The previous numbers indicate a bias of development towards capacity installation rather than towards improvements in the efficiency of electricity generation. Of course, building additional capacity involves much shorter lead times than developing new technology or electricity infrastructure to improve capacity factors. However, the four countries analysed here share a trajectory of consistent capacity expansion for the last decade. Still, within this period, average capacity factors of wind farms built after 2005 have been stagnant (IEA, 2014c). Advances in wind turbine design, such as an increase of nominal capacity factors from an average 25.5% in 2000–2005 to an average 29% in 2006–2012, have not been enough to overcome the fall of electricity generation due to the expansion towards low wind quality sites and a lack of network adaptation (IEA, 2014d).

Wind power expansion has been stimulated by cost reductions realised through increasing returns to adoption obtained from rapid growth in the last decades (Blanco, 2009; IEA, 2014c; Lewis

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Table 3
Wind power capacity installations and utilisation.

Country	*WEG* in 2005 (GWh)	*WEG* in 2011 (GWh)	*IGC* in 2005 (GW)	*IGC* in 2011 (GW)	*RCF* in 2005	*RCF* in 2011	*FH* in 2005	*FH* in 2011	*WCU* in 2005	*WCU* in 2011
China	2028	73,200	1.3	62.4	18%	13%	23%	22%	80%	62%
US	17,811	120,177	8.7	46.0	23%	30%	30%	34%	78%	88%
Germany	27,229	46,500	18.4	29.1	17%	18%	26%	28%	65%	66%
Spain	21,176	42,374	9.9	21.7	24%	22%	27%	25%	91%	89%

Source: own elaboration, data from CWEA (2013), EEA (2009), EIA (2014), GWEC (2012), IEA (2014c), IWES (2014), Schwabe et al. (2011), Wiser and Bolinger (2013).

and Wiser, 2007). But this has been focused on capacity building. Evolution in electricity production and generation efficiency is lagging behind as shown by RCF levels (see Table 3). Consequently, performance of wind power systems is not entirely satisfactory. In financial terms, a low efficiency of electricity generation reduces profitability and enlarges payback times of investment. In environmental terms, idle wind power generation capacity represents foregone opportunities to reduce GHG emissions.

Next to the technological limits of wind turbines, wind quality determines capacity utilisation. Higher wind speeds generate higher energy output and blow more consistently. Previous studies indicate that a doubling of wind speed can increase power output of a wind turbine by a factor of eight (EEA, 2009), whereas a more consistent wind blow facilitates transmission scheduling and grid integration (Rahimi et al., 2013).

To account for these differences in terms of wind quality, we calculate the share of capacity utilisation of wind power (WCU) considering the wind regimes of each country studied, as follows:

$$WCU(t) = \frac{WEG(t)}{IGC(t)*FH(t)}$$

Here FH corresponds to a factor of wind quality calculated as the percentage of the number of hours in a year when wind power was available to run turbines at full capacity. Hours are measured for onshore wind turbines with on average 80 m hub height.

The percentage of capacity utilisation, as shown in Table 3, is based on wind turbine nameplate capacity and estimated wind regime. The differences between the realised capacity factor (RCF) and the wind regime (FH) indicate that not all the available wind power was used, that is, wind farms have not worked at full power during all possible hours.

Even though the performance of wind turbines depends on location (Chowdhury et al., 2013), there is wide agreement that modern onshore wind turbines in mature markets can achieve a working hours rate of 97% or more (Blanco, 2009; IEA, 2014c). As a matter of fact, the restrictions to electricity generation imposed by wind regimes can be overcome by adequate wind turbine designs, system operation technologies and market integration mechanisms. These will be discussed in following section.

3.2. Possible explanations for capacity utilisation of wind power

Among the various factors that condition wind electricity generation, here we focus on the most important ones for the current rates of capacity utilisation, namely: capacity factors, system flexibility and market integration (as summarised in Table 4). The goal is to identify factors that affect capacity utilisation, and thus explain the variation found among the countries studied. The analysis uses data from relevant energy agencies in each country, as well as insights from studies in the scientific literature.

3.2.1. Wind turbine design evolution

Between 2005 and 2011, variations in *RCF* values differed among the countries studied. Germany and Spain showed narrow ranges, while China and the US showed wider ones. The lower *RCF* variation in Germany and Spain can be explained by the small range of variance of wind regime in these countries. With relatively small territories, additions of wind power installations in Germany and Spain take place in locations with similar wind conditions than in the ones previously exploited. The improvement of *RCF* in Germany is mainly explained by repowering,[14] a trend that is yet to start in Spain. In 2011 only, repowering had accounted for approximately 17.8% of new installations in Germany, increasing average output by a factor of 2.5 in the renewed wind farms (GWEC, 2012). In Spain, the estimated potential for repowering is 2.3 GW, corresponding to wind power installed capacity in commercial operation for a period of at least 13 years (Colmenar-Santos et al., 2015). However, repowering is expected to play a role in the industry only after 2016, when public funding is expected to become available (Del Río et al., 2011).

China and the US show very different cases characterised by large and opposite *RCF* variations. Such a disparity comes as a natural consequence of the exponential rates of growth experienced by wind power in these countries. Whereas Germany and Spain roughly doubled their installations and generation capacity within the 7 years analysed, in the US these have grown by over 400% and in China by more than 350% in the same period. The fact that the Chinese *RCF* decreased over time while the North-American increased can be explained by differences in the wind power technology and the electricity system of each country.

China's capacity factor has historically been among the lowest in the world. In the last years, capacity factors continued to fall mainly for three reasons. First, the long distance between sites with best wind quality, mostly located in the North of the country, and main consumption centres concentrated in the southeast, has limited wind power generation through transmission losses and forecast errors (Yang et al., 2012). Second, wind farms expansion turn towards low wind speed locations which has pushed full load hours further down since 2010 (Zhao et al., 2013). And, third, faulty wind turbine design. On the one hand, Chinese installations are dominated by turbines with medium to low capacity: 1.5 MW turbines respond for 64% of total installations, followed by 2 MW and 2.5 MW with 26.1% and 6.6%, respectively (Li et al., 2015). On the other hand, the majority of the wind turbines operating do not meet the technical requirements to be connected to the grid which have reduced the share of wind installations connected to the grid from 84.48% in 2005 to 75.36% in 2011 (Zeng et al., 2015).

In contrast, the increase in *RCF* in the U.S. can be attributed mainly to technological improvements in wind turbine design and better wind farm siting. The design of the average wind turbine installed in the US evolved from 1.4 MW turbine nameplate and 70 m hub high in 2004–2005 to 2 MW and 100 m high in 2011,

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[14] Repowering refers to the process of replacing existing wind turbines with new turbines that either have a larger nameplate capacity or higher efficiency of electricity generation.

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Table 4
Summary of determinants of capacity utilisation.

		China	United States	Germany	Spain
Capacity factor	Turbine design	Low nameplate capacity	High nameplate capacity	Mixed nameplate capacity Repowering in place	Medium nameplate capacity
	Location	Average wind country Expansion towards low wind regime sites	Average wind country Expansion towards low wind regime sites	Low wind country Expansion towards sites with similar wind regime	High wind country Expansion towards sites with similar wind regime
System flexibility	Network infrastructure and management	Low capacity of transmission lines Inadequate wind turbine technology	Large investment in transmission lines High accuracy of wind generation forecasts Nodal dispatch control	Large investment in transmission and distribution lines Early network adaptation to wind power	Real-time communication Centralisation of grid operation
	Portfolio diversity	Coal and hydropower	Decentralised wind power Gas and hydropower	Coal, gas, solar PV and hydropower	Coal, gas, solar PV and hydropower
	Demand Side Management	NA	Yes	Yes	Yes
Market integration	Balance of dispatch	Market for ancillary services non-existent	Market for ancillary services partially developed	Market for ancillary services base developed	Market for ancillary services developed
	Time of response	Long term contracts	5′ for some spot markets	45′ for spot markets	15′ for spot markets
	Local marginal pricing	NA	ERCOT (Texas)	EpexSpot market	EpexSpot market
	Curtailment control	At power generator level	At the wind turbine level	At the wind turbine level	At the wind turbine level
	Cross-border trade	Among ‘regional markets’	Among system operators (mostly at the State level)	CWE region and the Northern region	Mainly with Portugal

Information in this table is based on CWEA (2013), DOE (2010), EEA (2009), EIA (2014), IEA (2014a, 2014b, 2014c, 2014d), EC (2014), IWES (2012), IPCC (2012), NREL (2013), Wiser and Bolinger (2013).

resulting in larger and more constant energy output (Wiser and Bolinger, 2013). For example, 26.5% of installed capacity in 2011 corresponded to turbines with rotor diameters of 100 m or larger, compared with only 10% in 2010 (AWEA, 2012). Additionally, the ratio of nameplate capacity to swept area declined, which improved energy capture. In the last decade, annual energy production per square metre of swept rotor area (MW/m^2) has shown yearly increments of 2–3% (EEA, 2009). At the same time, wind farm siting has also positively contributed to improve capacity factors. With more accurate knowledge about wind regimes and turbine design adequacy, wind farm layouts have been refined, leading to capacity factor improvements of up to 6.4% (Chowdhury et al., 2013). As a result, the US has achieved higher capacity factors for wind farms — in spite of the recent expansion towards lower-quality wind resource sites.

3.2.2. Flexibility of network infrastructure and operation

In terms of system flexibility, the most important barriers for increasing wind power capacity utilisation in the countries studied are related to network infrastructure and operation. A problem common to the four countries is the speed of networks expansion. Building transmission and distribution infrastructures require much more time than building wind farms. One reason is that creation of transmission lines involves extended land acquisition (Fernández Fernández et al., 2013; Yang et al., 2012). Network issues differ among countries due to geographical features, technologies implemented and electricity market structure.

In China, the combination of this time delay to build grid infrastructure and a high level of investment in installations is a main cause of a low (and even falling) rate of capacity utilisation. In addition, low technical standards for generators to connect to the grid also play an important role in limiting wind power capacity utilisation. The lack of grid control and management technologies not only decreases the input of wind-generated electricity but also reduces the overall reliability and security of the electricity system. As a result, China has the highest curtailment rates worldwide, 17.5% in 2011 and 21.7% in 2012 (Li et al., 2015). Between 2010 and 2011 only, 273 major incidents of turbines unexpectedly going off-line from the grid were registered, increasing losses in the amount of electricity fed into the grid (Schuman and Lin, 2012). One of the main difficulties is the absence of “Low Voltage Ride Through” (LVRT)[15] technology in most wind turbines installed in China, which further reduces the overall network resilience to the common variations in wind-electricity flows (GWEC, 2012a).

In contrast, in the US, expansion of installation capacity occurred simultaneously with capacity utilisation growth. This was pushed by two big forces to overcome network barriers to wind power integration: investment in transmission lines and improved operations management. Between 2007 and 2012, more than 2300 miles of new transmission lines were added yearly, compared to less than 1000 miles between 2000 and 2006. This was the result of a conjoint effort of States, grid operators, utilities, regional organisations, and DOE (Wiser and Bolinger, 2013). In Texas, for example, addition of transmission lines helped the main electricity system operator, ERCOT, to reduce curtailment levels from 17% in 2009, to 8–9% in 2010–2011 (NREL, 2013). Regarding operational barriers, US system operators are in the forefront of development of grid management technologies. Built upon the information of wind farms and grid operation assembled during the last decade, these management technologies enable significant improvements in forecasting accuracy and dispatching control (Porter et al., 2013). With higher forecast and control accuracy, system operators can increase the volumes of wind electricity dispatched by reducing response times. For instance, regions with fast energy markets might change the dispatch schedule within a 5 min period, while other regions often use hourly schedules (Gil et al., 2012). Shorter times of response in electricity markets can decrease the number and quantity of curtailments, maintaining the quality and security of the electricity supply, and at the same time maximising wind power dispatch.

Network adaptation to wind power in Germany started already in 2003 with the introduction of a Grid Code aimed at adapting grid requirements to wind turbine characteristics as well as to specific control and protection rules. This involved setting basic rules to assure network flexibility, including: technological standards for

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[15] LVRT is a technology that enables wind turbines and large wind farms to remain online when system voltage drops, instead of tripping offline; it is a requirement for grid connection in the US and Europe (IEA, 2014c).

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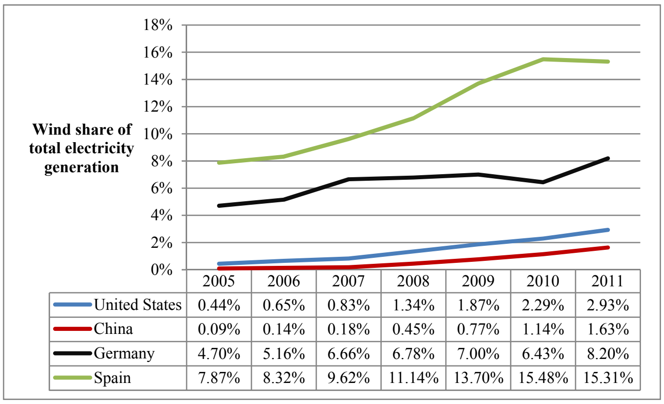
wind turbines (e.g. embedded LVRT technologies and provision of ancillary services like voltage and frequency control), and intelligent system protection devices to ensure a minimum loss of wind power and to guarantee fast recovery of normal operation (Erlich et al., 2006). These ended up influencing the wind power industry worldwide through the exports of German turbines and returns to scale from the quick expansion of the domestic grid. Germany has consistently amplified transmission and distribution lines with investments of more than 27 billion between 2007 and 2011 (Groebel, 2013). As a result, curtailment levels have been kept remarkably low, namely 0.2% in 2009 and 0.34% in 2010 (IWES, 2012).

With the highest levels of capacity utilisation among the countries studied, Spain is considered a benchmark of network flexibility. This achievement is mainly due to electricity system operations. Since 2006, transmission system operators (TSO) require real-time communication with wind farms so that the relevant conditions of operation can be observed and generation can be controlled at all times (Holttigen et al., 2013). 99% of the high voltage transmission lines in Spain are controlled by the Red Elétrica Española. This TSO centralises the operation of renewable energy sources in the country, receiving information from wind parks, while controlling 96% of wind generation capacity installed. It allows for adaptations of power generation within 15 min (De La Torre et al., 2012). This degree of precision to change wind power dispatch at different points of the grid enables the operator to avoid curtailment and energy transmission losses, thus leading to optimisation of capacity utilisation.

3.2.3. Penetration level, price signals and ancillary services

Market integration becomes increasingly difficult with higher levels of wind power penetration. In this regard, Germany and Spain are considered to have achieved high penetration levels with wind power responding to at least 4% of the total net electricity supply since 2005; however, China and the US markets are still in their infancy, with penetration levels around 2% (Fig. 1). Even though penetration levels have risen in all four countries, the gap between installed power and capacity utilisation remained wide.

There are many approaches that can explain the markets' ability to efficiently absorb high levels of wind power. Markets positively contribute to managing larger balancing areas and sources, pooling bids and bridging different regions and countries. For wind power, two aspects of market integration are important: long-term market signals must be able to induce system adaptation to be built; and the market must generate sufficient revenue to guarantee financial viability (Benatia et al., 2013; Holttinen et al., 2011). This depends, among other mechanisms, on price signals to wind power generators as well as to conventional generators. Markets that warrant priority to wind power generators to sell electricity while providing backup for shortages from conventional sources accommodate the natural characteristics of wind while reflecting the cost of overall system reliability.



	2005	2006	2007	2008	2009	2010	2011
United States	0.44%	0.65%	0.83%	1.34%	1.87%	2.29%	2.93%
China	0.09%	0.14%	0.18%	0.45%	0.77%	1.14%	1.63%
Germany	4.70%	5.16%	6.66%	6.78%	7.00%	6.43%	8.20%
Spain	7.87%	8.32%	9.62%	11.14%	13.70%	15.48%	15.31%

Fig. 1. Wind as share of total electricity generation.
Data from EIA (2014).

Within the period studied, Germany and Spain have used the merit order effect to grant priority of dispatch to wind-generated electricity. Wind power is delivered to the grid whenever produced, regardless of demand. Curtailment is allowed for security reasons, such as to avoid grid instability. Feed-in tariff payments are maintained when electricity losses are caused by constraints of grid infrastructure. So far, this experience in Germany and Spain has led to a decrease in average wholesale electricity prices. The reason is that the merit order effect, by prioritising subsidised low marginal cost wind power, tends to push out of the most expensive electricity generators (Holttinen, 2012; Ketterer, 2014).

Another positive characteristic to increase capacity utilisation is the fact that both these countries benefit from flexible backup energy sources and established ancillary markets (Nicholson et al., 2010). Cross-border trade has increased in Germany specially since 2009 with the creation of the European Market Coupling Company, and since 2010, with the electricity market coupling between countries in the so-called CWE region (Belgium, France, Luxembourg, and the Netherlands) and the Northern region (Denmark, Sweden and Norway). Electricity flows among these countries are now jointly optimised with electricity exports from lower-price to higher-price regions (BMU, 2012). Spain enjoys a highly responsive backup system due to the centralised operation (as discussed in the previous section). Moreover, it also counts with good exchange capability with Portugal (De La Torre et al., 2012).

Limitations to market integration in China arise from the regulatory framework. The lack of separation between the political and regulatory authorities submits market efficiency to political compromises. The National Development and Reform Commission (NDRC) controls China's macroeconomic policy and regulates energy prices, mainly to control inflation, make Chinese exported goods more competitive pricewise, and ensure domestic social stability (Qiu and Li, 2012). Government driven, wind farm constructions are, in several cases, planned regardless of transmission capacity (Zeng et al., 2015), driven by factors disconnected to energy output, such as GDP growth, tax revenues or even achieving the necessary wind capacity required by local regulation to build new coal-fired power plants (Lam et al., 2013).

Unlike the centralised market regulation, the electricity transmission network is fragmented with the physical grid divided into regional grids managed independently (Kahrl et al., 2011). Hence, the Chinese market has very low levels of integration among regions, almost completely missing the benefits of balancing dispatch among different locations. Until 2009, prices of wind power in China were determined case by case through a bidding policy. But by privileging the lowest bidding prices this mechanism has exacerbated competition and reduced investors' enthusiasm. Subsequently, a policy based on a fixed price was introduced involving setting four types of wind power benchmark prices across the country (Li et al., 2015). This has created new barriers to increasing capacity utilisation since it blocks trade among different "price regions" (Yuan et al., 2014).

In the U.S., wind power markets are regulated at the state level. However, these are highly integrated and flexible since more than 60% of the total electric output at the country level is managed through markets that operate on 5-min response time (Milligan et al., 2011). This inter-state integration brings several positive contributions to higher capacity utilisation of wind power, such as: the enlargement of balancing area; the provision of ancillary

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services due to short dispatch intervals; and the potential of inter-regional scheduling as shorter response times enable more efficient dispatch planning for importer and exporter (Milligan and Kirby, 2010). Nevertheless, only a minor share of wind power is typically traded in short-term spot markets in the U.S. Historically, around 60% of wind energy has been sold through long-term Purchase Power Agreements (PPAs) for an average period of 20 years. These have performed well as a hedge against price variations from fossil fuels, a mechanism that reproduced a merit order effect stimulating the maximisation of capacity utilisation. Nevertheless, this is a contribution to capacity utilisation with variable effectiveness. As shown by the recent fall of wholesale electricity prices (driven by lower natural gas prices), average wind PPA prices have suddenly gone out of the wholesale power price range on a nationwide basis (Wiser and Bolinger, 2013). This undermines the financial benefits of wind electricity, potentially reducing its input into the grid.

4. Implications for GHG emissions and policy recommendations to narrow the capacity–generation gap

Wind power generates environmental benefits primarily from displacing the emissions from fossil fuel-based electricity generation. Wind-generated electricity entails 28.1 times[16] less emissions than coal, currently the first source of electricity generation worldwide (IEA, 2014). However, these potential environmental benefits of wind power have not been realised because power generation capacity is only partially used (as shown in Section 3). This becomes more problematic as wind power participation in electricity supply grows. Present prospects point to at least 20% of electricity supply from wind in the countries studied. Hence, the capacity–generation gap, if maintained, will increase the amount of missed reductions of GHG emissions.

Our findings, as summarised in Table 4, indicate that capacity–generation gaps of wind power are country specific. Next to geographical conditions and technological limitations, electricity generation from wind is determined not only by direct subsidies for deployment, but also by balancing and grid regulations (IEA, 2014d; Holttinen et al., 2011; Klessmann et al., 2008; Hulle et al., 2009). Policy solutions to narrow this gap need to simultaneously tackle three barriers to capacity utilisation, namely: low capacity factors, insufficient system flexibility and limited market integration (see Section 3 for details). Without addressing these barriers, further expansion of wind power installations will tend to enlarge capacity–generation gaps. Analysing the four countries with the largest wind power installations (2005–2011) has allowed us to identify regulations that have successfully improved wind power capacity utilisation (Table 5), and derive policy recommendations to reduce the capacity–generation gap.

Capacity factors can be improved by better locations in terms of wind regime and network operation, and design of wind turbines and wind farms. Regulation of locations of wind farms can help by directing wind farms towards sites with best wind regimes and most suitable network connections (Boccard, 2009; Burke and O'Malley, 2011). Next to increasing electricity output due to better wind resources, optimal location can improve network operation, e.g. reduce electricity flow congestion. In relation to wind turbines and wind farms design, subsidies based on generation efficiency rather than installed capacity can stimulate power generators to opt for the most energy efficient option rather the cheapest one. Since the early development of their wind power industries, Germany and Spain have stimulated high capacity factors by establishing minimum standards for wind turbines technologies (Erlich et al., 2006) and, more lately, repowering programmes to replace low performing wind turbines (Del Río et al., 2011). An additional, recent instrument used by these countries is to set payments of feed-in tariffs in proportion to wind regime quality. This is aimed to stimulate investors to optimise location and avoid problems with lack of grid connection or wind turbine shadowing due to low quality wind regimes (Del Río, 2012; Nordensvärd and Urban, 2015).

To improve system flexibility, policy needs to enhance coordination among wind power generators, system operators and grid infrastructure. An initial requirement is to align the expansion of wind power installations with overall system development. Auction mechanisms[17] may provide an attractive solution since they enable to control the volume of additional installations while keeping prices competitive (del Río and Linares, 2014). Auctions also facilitate information about the location of future generators which optimises investments in grid infrastructure. Among the countries studied, the ERCOT in the US is one of the best examples of successful regulation resulting in a balanced expansion of wind power installations and transmission infrastructure. The Public Utility Commission of Texas has defined five areas as competitive renewable energy zones, where the building of transmission lines precedes the full development of wind power capacity. Here, one of the enabling factors is that policy design has facilitated financing by allocating all transmission costs to load (Milligan et al., 2015). As a result, a plan to construct new transmission was developed to guarantee the dispatch of additional 18.5 GW of wind power while reducing the volume of curtailments (IEA, 2014c). In parallel, electricity market regulation can facilitate system operation by stimulating the use of demand-side management mechanisms and creating an incentive for conventional generators to provide ancillary services (see Section 2). In Spain, for example, regulation has contributed to shorten response times by: establishing mandatory hourly output forecasts from generators with installations over 10 MW; as well as an economic incentive to acquire fault-ride through capability of up to 5% for kWh generated for 4 years[18] (RD, 2007).

In terms of deepening market integration, policy can provide an immediate contribution by increasing the area size over which the system is balanced in real-time. This can increase the utilisation of wind power capacity, namely through geographical smoothing and higher economies of scale (Benatia et al., 2013). At the country or region level, the harmonisation of regulations, such as protocols and procedures across different system operators, would extend and improve coordination among different areas (Baritaud, 2012). At the international level, similar type of benefits could be achieved through integration of national renewables policies and system operation regulations. This can be illustrated by the European regulation creating the European Network of Transmission System Operators (ENTSO-E) in 2009. Since then, the ENTSO-E has improved the coordination among the electricity markets of the 34 member countries, promoted further standardisation of regulations, and increased market transparency and integration.

Large-scale deployment of wind power leads to more volatile, real-time power flows which add requirements to the energy

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[16] Given that the average life cycle GHG emissions for wind energy is 34.1 g CO_2-eq/KWh (Nugent and Sovacool, 2014) and for coal to be 960 g CO_2-eq/KWh (Sovacool, 2008).

[17] In auction mechanisms, both price and quantity are determined in advance of the decision to build a wind farm, namely under a public bidding process.

[18] Based on the estimated average total system cost, which includes all the costs of the system in a year (such as costs of generation, transmission, distribution, retail, etc.).

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Table 5
Examples of policy measures to reduce capacity–generation gap of wind power (2005–2011).

Policy focus	Policy measures	Examples
Capacity factor	Regulation of wind farms' location	None of the countries studied have regulated wind farm siting specifically in relation to the quality of wind regimes.
	Standards for wind turbines technologies	Germany and Spain: wind turbine certification and grid code[a] standards as requisites for approval of wind power projects.
System flexibility	Alignment between expansion of wind power installations and electric system development	US (ERCOT): definition of areas as competitive renewable energy zones, where grid infrastructure building takes place before full potential of wind power installations is realised.
	Demand-side management mechanisms	Spain: regulation establishing technical obligations (e.g. production forecast, fault-ride through capability) to improve control of wind power generation and dispatch into the grid.
Market integration	Incentives to geographical expansion of market for balancing services	Germany and Spain (Europe): since 2009, Germany and Spain benefit from the European Network of Transmission System Operators (ENTSO-E), which co-ordinates 41 national transmission systems operators (TSOs) from 34 countries.
	Harmonisation of regulations	Spain: creation of a specific national control centre for renewable technologies (the CECRE – Control Centre for the Special Regime), with mandatory connection for all wind power generators.

Information in this table is based on Abbad (2010), Brunes and Ohlhorst (2011), Del Río (2012), DOE (2008); ENTSO-E (2012); EWEA (2010); Hulle et al. (2009); IEA (2014c); IRENA (2012); Lew et al. (2010); Milligan et al. (2015); RD (2004); RD (2007) and Wu et al. (2014).

[a] Grid code typically includes technical specifications for power load such as voltage and frequency.

system in order to secure electricity supply. Ancillary services, network infrastructure and market remuneration need to be adapted to wind power dynamics in a cost and time effective way. So far, because wind penetration levels have been maintained at an upper limit of 10–15% of total electricity generation (for certain countries and period analysed here, namely Germany and Spain), managing the technical operation of power systems has been possible without major changes on the energetic system and without using its full installed capacity. But with continuous growth of wind power installations and more pressing need to reduce GHG emissions, a full adaptation of the electricity system is required. It is clear that the challenges created by wind power intermittency and dispersed geographical distribution can only be resolved with policy support. Yet, no single policy solution has emerged until now, arguably because of the specific and changing dynamics of the each energy system.

5. Conclusions

This paper has analysed the mismatch between installed capacity and actual electricity generation of wind power. It studied the evolution of wind power installations and electricity generation in China, US, Germany and Spain. Levels of capacity utilisation of wind power installations were estimated and its drivers were identified. Despite differences in terms of development of wind turbine design, flexibility of network infrastructure and operation, and the level of wind power penetration, all four countries studied show a constant, if not rising, capacity–generation gap in wind power.

With the largest additions in capacity installations, China and the US showed distinct performances in capacity utilisation. In China, constraints on grid connection and lack of market incentives to integration led to a decrease in capacity utilisation, from 80% in 2005 to 62% in 2011. In the US, increasingly advanced wind turbine technologies and grid management techniques improved capacity utilisation, from 78% in 2005 to 88% in 2011. Germany and Spain represent more mature markets. In Germany, repowering of wind farms has contributed to maintain capacity utilisation stable at around 65%. In Spain, development of system operation techniques and advances in wind forecasting have been responsible for sustaining capacity utilisation at a very high level of about 90%.

Several policies can contribute to a better balance between power generation capacity and capacity utilisation of wind power. Electricity market regulation and policies promoting system flexibility play a key role. Policy support to wind power should focus not only on expanding capacity installation, but also on increasing the efficiency of electricity generation. This can be achieved through the development of better performing technologies (wind turbines, system operation techniques, wind forecast methods) as well as extended integration of wind power electricity into the (inter)national electricity system. In this way, the net electricity generation from the overall system could be increased, contributing to further and cost-effective reduction of GHG emissions.

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