LETTERS
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Potential contribution of wind energy to climate change mitigation

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It is still possible to limit greenhouse gas emissions to avoid the 2 °C warming threshold for dangerous climate change[1]. Here we explore the potential role of expanded wind energy deployment in climate change mitigation efforts. At present, most turbines are located in extra-tropical Asia, Europe and North America[2,3], where climate projections indicate continuity of the abundant wind resource during this century[4,5]. Scenarios from international agencies indicate that this virtually carbon-free source could supply 10–31% of electricity worldwide by 2050 (refs 2,6). Using these projections within Intergovernmental Panel on Climate Change Representative Concentration Pathway (RCP) climate forcing scenarios[7], we show that dependent on the precise RCP followed, pursuing a moderate wind energy deployment plan by 2050 delays crossing the 2 °C warming threshold by 1–6 years. Using more aggressive wind turbine deployment strategies delays 2 °C warming by 3–10 years, or in the case of RCP4.5 avoids passing this threshold altogether. To maximize these climate benefits, deployment of non-fossil electricity generation must be coupled with reduced energy use.

Kinetic energy in the atmospheric boundary layer exceeds both present world electricity and energy demand[6,8]. Estimates of the present technical potential for wind energy span an order of magnitude owing to the range of assumptions used (17–320 TW; ref. 6), and the global extractable resource may be >428 TW (ref. 9), which greatly exceeds present total primary energy supply (TPES) of 18 TW (ref. 9). Thus, there is opportunity for substantial expansion of wind-generated electricity supply from today's level (~0.2% of TPES (ref. 6)). Indeed 'on a global basis, at least—technical potential is unlikely to be a limiting factor to wind energy deployment'[6]. Further, the large increase in both raw materials and rare metals required for large-scale expansion of wind is manageable[10], and 'no insurmountable long-term constraints to materials supply, labour availability, installation infrastructure or manufacturing capacity appear likely if policy frameworks for wind energy are sufficiently economically attractive and predictable'[6]. For example, rare-earth oxides used in the 20% of wind turbines with permanent magnet generators have known reserves of ~1,000 years supply at present consumption levels[2].

About three-quarters of global wind power capacity (282 GW at the end of 2012) is installed between 30° and 60° N in Europe, North America and China[2,3]. Although site-specific near-surface wind speeds (and wind resources) are determined by multiple scales of motion, wind regimes in these high-resource locations are largely dictated by the track, frequency and intensity of mid-latitude cyclones[11]. Whereas smaller-scale thermodynamic systems such as storms cells and thermotopographic flows are not well described by Earth system and regional climate models, larger cyclones and hemispheric-scale teleconnections associated with intra- and inter-annual variability of wind speeds are comparatively well understood and modelled[11,12] (Supplementary Fig. 1). The 'storm tracks' that mid-latitude cyclones follow are, to a first approximation, determined by Equator-to-pole temperature gradients that have been decreasing since 1870 (in a manner consistent with global warming), and there is evidence of a resulting slight poleward shift in cyclone tracks[11]. However, the signal-to-noise ratio is small, and climate change projections for the main regions of wind energy penetration developed using climate model ensembles, empirical and hybrid downscaling, indicate a stable resource to mid-century and probably beyond[4,5] and thus over the projected lifetime of wind power plants (20–30 years).

On the basis of this body of research, we quantify whether using this low-carbon-dioxide (CO_2)-emitting electricity generation source can impact the magnitude of climate change by lowering climate forcing. To facilitate interpretation of our results, we present them within the context of the Intergovernmental Panel on Climate Change (IPCC) RCPs and in terms of a goal of avoiding/delaying the 2 °C warming limit often considered the lower threshold for dangerous climate change[1].

Electricity generation from any source affects the local and/or global environment. For example, coal-fired electricity generation is associated with externalities beyond release of CO_2, including an average of 24.5 deaths, 225 serious illnesses and 13,288 minor illness per terawatt hour of electricity generated[13]. Large wind farms, like major cities and forests, extract momentum from the air and add turbulence, thus altering the meteorology downwind. However, detailed *in situ* and remote-sensing measurements at operating wind farms show limited impacts on, for example, near-surface temperature beyond a few kilometres[14]. Modelling of wind deployment of 5 to >20 times TPES, and thus in excess of the wind energy scenarios considered here, resulted in only moderate meteorological impacts of <1% and 0.1 K change in zonal mean precipitation and surface temperature[9]. Modelling of 2020 wind energy scenarios for Europe also resolved very small downstream impacts that were statistically significant only in winter (to ±0.3 °C change in 2-m temperature and to 5% increase in precipitation)[15]. Thus, externalities from large-scale wind energy deployment seem modest.

TPES more than doubled between 1973 and 2011 (ref. 16). In 2011, TPES was ≥540 EJ, of which renewables (excluding biomass/biofuels) contributed ~3.3% (ref. 16). Electricity production increased ~3.4% per year from 1973 to 2011 when it reached 22,000 TWh (ref. 16; 68% from fossil fuels), and annually consumes ~25% of global TPES (ref. 17). All plausible future scenarios indicate TPES and electricity generation increasing to 2035 (refs 7,16). The International Energy Agency (IEA) projects

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Table 1 | Scenarios of potential electricity generation from wind energy to 2050 shown in terms of terawatt hours and percentage of total electricity generation.

		Wind electricity generation (TWh) (approximate percentage of the total electricity generation)				
Scenario name	**Brief description**	**2011 or 2012***	**2020**	**2030–2035**	**2050**	**Source, year and reference**
Current Policies/6DS	No policy changes from 2013	434 (2.0%)	1,195 (4.2%)	2,251 (5.6%)		IEA 2013 (ref. 18)
New Policies/4DS	Wind energy generation increases 6% per annum 2001–2035	434 (2.0%)	1,326 (4.8%)	2,774 (7.4%)		IEA 2013 (ref. 18)
450 Scenario	Limit emissions to stabilize atmospheric CO$_2$ at 450 ppm	434 (2.0%)	1,441 (5.4%)	4,337 (13.4%)		IEA 2013 (ref. 18)
2DS	Radical transformation of energy system	527* (2.5%)		3,680 (11.4%)	6,150 (15%)	IEA 2013 (ref. 2)
HiRen	High penetration of wind, less nuclear and carbon capture and storage	527* (2.5%)		4,205 (13.1%)	7,250 (18%)	IEA 2013 (ref. 2)
Cat III + IV	Atmospheric CO$_2$ concentration in 2100 440–600 ppm			3,300	6,500 (13%)	IPCC 2012 (ref. 6)
Cat I + II	Atmospheric CO$_2$ concentration in 2100 <440 ppm			3,100	7,600 (14%)	IPCC 2012 (ref. 6)
New Policies	Wind energy markets flat	583 (3.5%)	1,439 (6.0%)	2,412 (8.0%)	4,264 (10.3%)	GWEC 2012 (ref. 30)
Moderate	Extends New Policies by including national/regional targets for renewable energy. Moderate wind energy growth	583 (3.5%)	1,863 (7.7%)	4,251 (14.1%)	8,736 (21.2%)	GWEC 2012 (ref. 30)
Advanced	Ambitious renewables and carbon emissions reduction. Wind energy growth starts at 21% and declines to 6% by 2030	583 (3.5%)	2,821 (11.7%)	6,678 (22.1%)	12,651 (30.6%)	GWEC 2012 (ref. 30)

There is some discrepancy in estimates of total present and projected electricity generation: according to the IEA, electricity generation in 2011 is ~22,120 TWh, but a different baseline is used for the GWEC estimates (~18,000 TWh). For comparison, projected total electricity generation in 2030 from the IEA Current Policies, New Policies and 450 Scenario are 40,100 TWh, 37,460 TWh and 32,256 TWh, respectively (see Fig. 1, top left inset, for electricity projections).

that annual electricity demand may exceed 40,000 TWh by 2035 (2.3% increase per year) and even the IEA 450 scenario indicates >30,000 TWh of generation by then[18] (Table 1).

Coal (rather than gas or nuclear) dominates present global electricity production, and is a key component of recently installed capacity[19]. At present, coal-fired electricity-generating plants (1,700 GW of capacity) provide 41% of world electricity (9,100 TWh annually), and coal combustion (heat and electricity) accounts for 41% of energy-related CO$_2$ emissions (13.8 Gt CO$_2$ per year; ref. 20). Using wind energy to replace coal gives the largest impact on CO$_2$ emissions and other externalities, and thus in the calculations presented below we assume that wind displaces coal generation. No electricity generation has zero life-cycle CO$_2$ emissions, but the emission debt from construction of wind power plants is small. Electricity generation of 1 kWh from wind is associated with CO$_2$ emissions of 8–20 g (ref. 6; from construction, transport, decommissioning and so on), but use of coal yields ~900–1,000 g CO$_2$ kWh^{-1} (ref. 13). Herein we assume that replacing coal-generated with wind-generated electricity reduces CO$_2$ emissions by ~886 g kWh^{-1}. The 300 GW of wind energy capacity installed at present generates about 2.5% of world electricity (~580 TWh annually)[2] and is thus associated with ~5 Mt CO$_2$ emissions (and 455 Mt CO$_2$ of avoided emissions)[2].

From 1991 to 2012 wind energy installed capacity grew 24% annually[2] (Fig. 1, top right inset). A range of projections for wind-generation of electricity have been developed for 2030 and beyond (Table 1 and see Methods). At the lower end, the IEA Current Policies scenario projects expansion of wind energy at a rate far below that during 1991–2012 such that electricity production from wind reaches only 2,250 TWh by 2035 (~four times that in 2013; ref. 2). This requires annual installation of 45 GW of wind energy, equal to installations in 2012, and thus for which manufacturing capacity already exists[2]. The higher projections indicate up to 50% wind-derived electricity generation by 2050 (ref. 6). The Global Wind Energy Council (GWEC) Moderate scenario (similar to IEA 450 Scenario) equates to annual wind-generated electricity production ~4,300 TWh by 2030–2035 (14% of total generation), and the GWEC Advanced scenario envisages ~6,700 TWh of wind-generated electricity by 2030–2035 (22% of total generation; Table 1 and Fig. 1). The installed capacity necessary to achieve these totals is a function of the capacity factor (see Methods). The degree to which wind intermittency presents a challenge to achieving these scenarios is a function of the spatial distribution of wind energy, the diversity of electricity generation, and the deployment/management/operation of the transmission grid. Penetration to 20% (as in the Moderate scenario) can probably be readily managed[6]. For the Advanced scenario, further grid

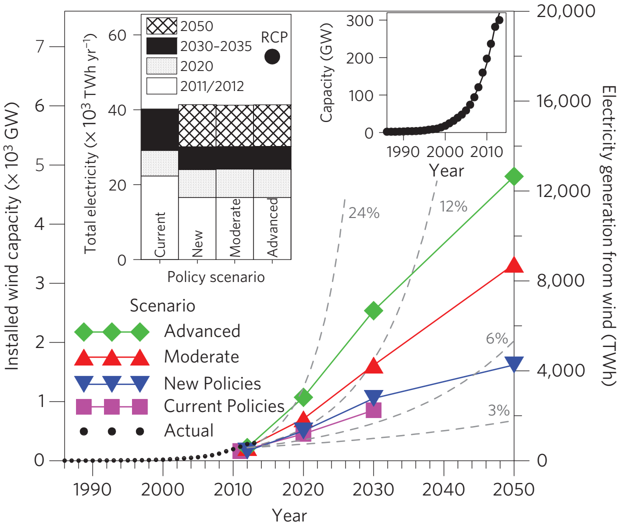

Figure 1 | Scenarios for expansion of wind energy installed capacity (gigawatts) and electricity generation (terawatt hours; assuming a capacity factor of 0.3, see Methods) from IEA Current Policies, New Policies[2] and GWEC Moderate, Advanced scenarios[30]. To contextualize the scenarios, trajectories of 3, 6, 12 and 24% annual growth are also shown. Top right inset: actual annual growth of wind energy (24% yr^{-1}) from the early 1990s to now. Top left inset: total electricity projections for 2020, 2035 and 2050 for IEA and GWEC energy scenarios. The RCP point indicates projected electricity supply in 2050 under the RCP scenarios (Supplementary Table 1).

management adaptation might be required along with natural gas generation, battery storage or demand management that may offset some of the avoided emissions of CO_2 assumed herein.

The transient climate response to cumulative carbon (C) emissions is defined as the global mean surface temperature change per 1,000 Gt C emitted and is ∼0.8–2.5 °C (ref. 1). On the basis of observed and modelled temperature response to cumulative CO_2 emissions, we assume that a 2 °C warming above pre-industrial temperatures (ΔT) is associated with anthropogenic emissions of ∼3.67 trillion tonnes of CO_2 (ref. 21), and thus the response function is 0.00054 °C/Gt CO_2 (ref. 1). Earth system model simulations indicate that passing ΔT of 2 °C is associated with CO_2 concentrations of 415–460 ppm (ref. 22).

The 2 °C warming threshold is used here as a simple metric of climate change, but projections of when this threshold might be passed are subject to a number of uncertainties (for example, climate sensitivity and natural climate variability). Uncertainty in the temperature response to cumulative CO_2 emissions derives from three main sources. First, uncertainty in anthropogenic cumulative C emissions so far[21]. Here we use 515 ± 70 Gt C to the year 2011 (ref. 1; Supplementary Fig. 10′). Propagation of the ±70 Gt C uncertainty in initial conditions shifts the passing of the 2 °C threshold by about ±7 years for RCP8.5. Second, the relationship between the global mean surface temperature response (ΔT) and total accumulated CO_2 emissions is assumed approximately linear[1] (to but not beyond peak temperature). However, this simple approach does not include feedbacks, and uncertainty in the response spans 0.0002–0.0007 °C per Gt CO_2 (equating to ΔT of 0.8–2.5 °C for 1,000 Gt CO_2 emitted[1]; Fig. 2). The third source of uncertainty is linked to the role of climate forcing from other gases. All RCPs that describe emission, concentration and land-use pathways[1] indicate that over three-quarters of climate forcing to 2100 derives from CO_2 (ref. 7). As shown in Fig. 2, limiting ΔT to 2 °C or less related to anthropogenic CO_2 emissions alone (with a probability of >33%, >50% and >66%) requires limiting cumulative CO_2 emission totals to 5,760, 4,440 or 3,760 Gt CO_2, respectively[1], but the amounts are reduced if non-CO_2 forcings are included.

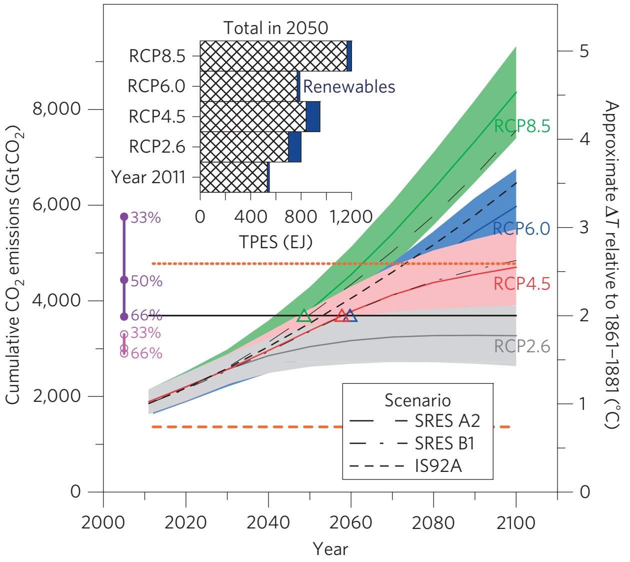

Figure 2 | Cumulative CO_2 emissions (CCE) and global mean temperature change for the IPCC RCPs (refs 26–29; shading denotes uncertainty associated with historical CCE (±70 Gt CO_2; page 27, ref. 1) and RCP anthropogenic CCE (Table AII.2.1a; ref. 1)). The horizontal black line indicates the Δ2 °C threshold associated with CCE ∼ 3,700 Gt CO_2 (TFE.8; ref. 1), assuming a temperature response of $\Delta T = 0.00054$ °C per Gt CO_2. To indicate the range of plausible ΔT for CCE ∼3,700 Gt CO_2, the orange dashes show ΔT for 0.0002 °C per Gt CO_2 and orange dots ΔT for 0.0007 °C per Gt CO_2. Open triangles mark the year the threshold is passed for each RCP (Table 2). The vertical purple line indicates the upper limit for CCE for $\Delta T < \Delta 2$ °C with a probability of 33%, 50% or 66% and the magenta line indicates the same limits if non-CO_2 forcing is included[1]. The inset bar chart shows total primary energy supply (TPES; exajoules) and the contribution from renewables.

The four RCPs (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) cover a range of radiative forcing values (including non-CO_2 climate forcing) ∼2.6–8.5 W m^{-2}, and ΔT by 2100 of ∼1.7–4.8 °C (Fig. 2). According to these RCPs, the 2 °C threshold is reached in 2049 (RCP8.5), 2060 (RCP6.0), 2058 (RCP4.5) and not in the RCP2.6 scenario (Table 2). In this RCP the atmospheric CO_2 concentration remains below 500 ppm and is 421 ppm in 2100 (ref. 1).

The RCPs can be achieved through assumptions about the energy mix based on detailed global energy models (see description in Methods and Supplementary Table 1). Only RCP2.6 and RCP4.5 include an increase in the fraction of TPES from renewables, and all project increased TPES (Fig. 3) and wind-generated electricity production (Supplementary Table 1). The energy scenarios with respect to wind-generated electricity in the RCPs are broadly comparable to the IEA Current Policies as shown in Table 1. To assess the potential climate impact of employing the wind energy deployment strategies described above, we began by deconvoluting the implicit role of wind energy in the RCPs to avoid 'double counting' (see assumptions in Methods). Removing wind energy from these scenarios and replacing it with coal-generated electricity (shown in Supplementary Table 1) changes the time to the 2 °C warming threshold by ≤1 year in RCP8.5 and RCP6.0, but by nearly 4 years in RCP4.5. This is partly because the penetration of renewable energy in RCP6.0 and RCP8.5 is small; for example, in RCP8.5 the level of electricity from renewables in 2050 is only twice that in 2012, although electricity use is almost double. Conversely, RCP4.5 incorporates a larger fraction of renewables and CO_2 emissions decline later in the century (Supplementary Table 1).

Table 2 | Year in which the 2 °C warming threshold (that is, $\Delta T \sim 2$ °C) is passed according to RCPs and a range of assumptions regarding the supply of wind-generated electricity (Table 1 and Methods).

	Wind scenarios			
Climate forcing	**As in RCP**	**Current Policies**	**GWEC Moderate**	**GWEC Advanced**
RCP8.5	2049 (4.5)	2049 (4.5)	2050 (4.3)	2052 (3.9)
RCP6.0	2060 (3.2)	2060 (3.2)	2064 (2.9)	2070 (2.6)
RCP4.5	2058 (2.5)	2058 (2.5)	2064 (2.2)	Beyond 2100 (1.9)
RCP2.6	Threshold not passed (1.8)	Threshold not passed. Decreases cumulative CO_2 emissions and ΔT by <0.1 °C (1.7)	Threshold not passed. Decreases cumulative CO_2 emissions and ΔT by ~0.3 °C (1.5)	Threshold not passed. Decreases cumulative CO_2 emissions and ΔT by ~0.6 °C (1.1)

Also shown in parentheses is ΔT (in degrees Celsius) at 2100 for each scenario combination (RCP and wind deployment).

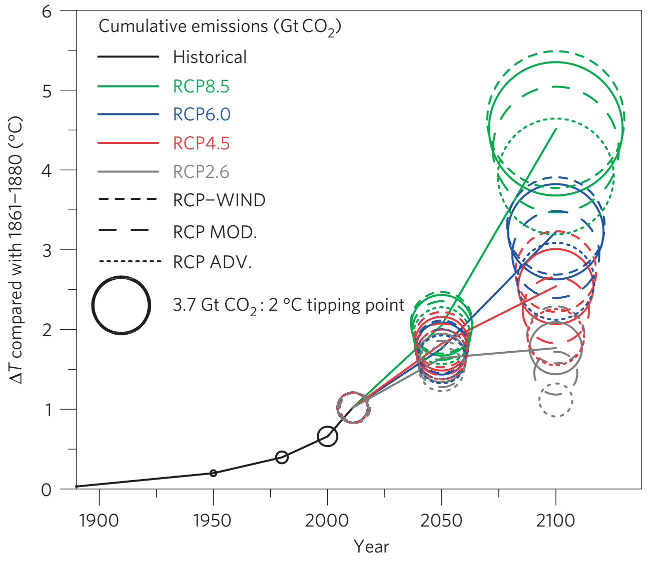

Figure 3 | Temperature change from 1861–1880 (ΔT, °C) due to cumulative CO_2 emissions (CCE) for the historical period and projected for four RCPs. The diameter of each 'bubble' scales linearly with the magnitude of CCE. The solid coloured circles and lines show baseline scenarios for each RCP (refs 26–29). The dashed coloured circles show RCPs with wind energy contributions removed (RCP–WIND) and replaced by coal (Supplementary Table 1). Results for RCP scenarios modified to include increased wind-generated electricity supply (replacing coal) according to the GWEC Moderate (MOD) or Advanced (ADV) scenarios are shown by the long dashed and dotted lines, respectively.

Using the GWEC Moderate wind scenario (Table 1) that is, increasing wind to 22% of electricity generation by 2050 (a level achieved or passed already by Denmark, Portugal and Spain[2]) extends the time to reach the 2 °C threshold by only 1 year in RCP8.5 (Table 2 and Fig. 3) because the increase in total energy use increases CO_2 emissions in 2100 to three times their present level and overwhelms the impact of the CO_2 emissions avoided by increased wind-generated electricity. Indeed, cumulative emissions by 2100 in this scenario amount to >7,500 Gt CO_2 (2,000 Gt C), which is half of the fossil fuel carbon reservoir (3,700–5,200 Gt C; ref. 1). The time to surpass $\Delta T = 2$ °C in RCP6.0 and RCP4.5 is extended by 4 and 6 years, respectively. As in the base RCP2.6 scenario the threshold is never reached, but implementing this wind deployment decreases cumulative CO_2 emissions from ~3,300 Gt CO_2 by 2100 in the original RCP to 2,700 Gt CO_2, decreasing ΔT by ~0.3 °C.

Adoption of the GWEC Advanced wind energy deployment scenario equates to an assumption that 30% of electricity consumption in 2050 (>12,000 TWh) derives from wind energy (that is, about 20 times that in 2012). Although this seems daunting, it is achievable by large-scale expansion (particularly offshore) of wind power plants combined with larger turbines with higher capacity factors[2] (see Methods). Applying this scenario for wind-generated electricity extends the time to reach the 2 °C threshold (Fig. 3 and Table 2) by only 3 years in RCP8.5, but by a decade in RCP6.0, and to beyond 2100 (or perhaps avoids it altogether) for RCP4.5 because cumulative emissions remain below 3,700 Gt CO_2. As in the base RCP2.6 scenario, the $\Delta T = 2$ °C threshold is never reached, but cumulative CO_2 emissions decrease to 2,100 Gt CO_2 decreasing ΔT by ~0.6 °C.

Obviously there are significant challenges involved in switching from fossil fuels to lower-carbon forms of electricity generation[2], and charting a road to a lower-carbon future should be done using a portfolio approach[18,23]. Nevertheless, employing plausible wind energy deployment scenarios can impact climate change. The cumulative impact of using wind energy (and/or other low-carbon electricity generation) is significant, particularly if it replaces coal, but critically depends on measures to curb overall energy demand. When combined with other strategies, aggressive deployment of low-carbon electricity generation (such as wind) can not only reduce the absolute magnitude of ΔT but substantially delay crossing of the 2 °C warming threshold (by over a decade or avoid it altogether), and thus buy time for other carbon emission reductions strategies to be employed[24,25].

Methods

Capacity factors. To convert from installed wind capacity (in gigawatts) to electricity generation (in terawatt hours), a capacity factor (the ratio of actual electrical power production to potential power production if operating at full nameplate capacity indefinitely) of 30% is assumed for wind energy. This is consistent with wind power plants operating at present[2]. Capacity factors for wind turbines range from 20–50% for onshore, 35–45% for offshore and exceed 30% for wind turbines deployed in the US (refs 2,6). Capacity factors are increasing owing to, for example, higher hub-heights, larger rotor diameters, expansion into higher-resources areas and better rotor design for lower wind speeds[6].

Wind energy scenarios. Although continued growth in wind energy installed capacity at present rates of 24% per year is unlikely to be sustained in the long-term, if it were continued wind energy could supply present electricity demand by 2040 (Fig. 1). Projections of technically feasible wind energy deployment for 2030 and beyond are shown in Table 1 and can be grouped into: Current Policies including IEA Current Policies and IEA 6DS, which project wind-generated electricity supply of ~2,250 TWh by 2035; New Policies including IEA 4DS and GWEC New Policies, which project wind-generated electricity supply of ~2,400–2,800 TWh by 2035; Intermediate Scenarios including IPCC scenarios Cat I + II and III + IV and IEA 2DS, which project wind-generated electricity supply of ~3,100–3,700 TWh by 2035; Moderate Scenarios including GWEC Moderate and IEA HiRen and 450 Scenario, which project wind-generated electricity supply of ~4,200–4,400 TWh by 2035; and Advanced Scenarios including the GWEC Advanced scenario, which projects wind-generated electricity supply of ~6,700 TWh by 2035.

The Moderate scenarios equate to supply of 14% of total annual electricity from wind by 2035. The GWEC Advanced scenario projects 22% of electricity from wind. Thus, both scenarios entail significant expansion of wind energy electrical power production (of 8–10 and 12–15 times present generation, respectively). The former is equivalent to: ∼9% annual expansion of deployed capacity for a fixed capacity factor 30%, or if coupled with a gradual increase in capacity factor from 30 to 35%, ∼6% annual increase in installed capacity. The energy scenarios shown in Table 1 are modelled to 2050. In this analysis, we extend these scenarios to 2100 by assuming that installation of wind capacity continues at the rate during the 2040s. In the Current Policies scenario, no further expansion of wind energy installed capacity occurs after 2030.

RCPs, description and assumptions. The IPCC RCPs are described in detail elsewhere[7,26–29]. In brief, RCP2.6 projects negative C emissions (that is, greater uptake from the atmosphere, than releases to the atmosphere) at the end of the century, leading to maximum emissions around 2030 (Fig. 2). This scenario assumes increases in energy efficiency, replacement of fossil fuels, addition of carbon capture and storage, and increase in bioenergy[29]. RCP4.5 stabilizes radiative forcing at 4.5 W m^{-2} (associated with CO_2 concentrations ∼650 ppm), peak CO_2 emissions in 2035, and projects declines in overall energy use combined with increases in the contribution from nuclear, bioenergy and renewables. In RCP6.0 policy intervention is modelled as a carbon tax to limit radiative forcing to 6.0 W m^{-2}. TPES increases to 838 EJ per year in 2100, but growth slows after 2060 leading to peak CO_2 emissions in 2060. In this scenario, penetration of renewable energy sources increases over the century (2000–2100) from 12.9% to 15.7% (ref. 26; Supplementary Table 1). RCP8.5 is intended to represent the baseline scenario and hence applies slow improvements in energy efficiency with a tripling of TPES (met for the most part by increases in use of fossil fuels, particularly coal), which results in continuously increasing CO_2 emissions to 2100 (ref. 27). Global CO_2 emission trends observed at present are consistent with those in RCP8.5 (ref. 25). The cumulative CO_2 emissions from the four RCPs extend over the range of emission scenarios used in previous assessments (SRES A2, SRES B1 and IS92A; Fig. 2). TPES and renewable fraction in 2050 are estimated from each RCP based on the scenario descriptions[26–29]. In 2011 hydropower generated about 3,500 TWh of electricity worldwide and other renewables generated about 1,000 TWh (ref. 16). For each RCP, we assume 10% of TPES from renewables derives from wind[27] (Fig. 2 and Supplementary Table 1).

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Author contributions

R.J.B. and S.C.P. designed the study. R.J.B. carried out most of the data analysis. R.J.B. and S.C.P. co-wrote the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.J.B.

Competing financial interests

The authors declare no competing financial interests.