Recent progress towards all-renewable electricity supplies

To the Editor — Policies to reduce carbon emissions from electricity generation will be crucial for negotiations at the UN climate conference (COP21) in Paris. In 2012, we presented data in *Nature Materials* on the contribution that photovoltaic (PV) power plants installed in Germany, Italy and the UK are making to reducing greenhouse emissions[1]. Here we update our analysis with three more years' worth of data, extending our study not only to other countries but also to wind power and bio-electricity generation. This analysis focuses mainly on the technical feasibility of an electricity supply based on all-renewable sources; more detailed cost considerations will be discussed in a forthcoming work.

Our considerations are partly based on results from the Kombikraftwerk (KKW) project — currently led by a co-author (K.K.) — which has studied, since 2006, the requirements for an all-renewable electricity grid in Germany. The first project (KKW1) scaled down the real-time demand of the German grid by a factor of 10,000 and compared it with the real-time power supplied by PV and onshore wind generators[2]. Software then instructed biogas electricity generators and a pumped hydro-storage element to balance supply and demand at all times throughout 2006. This analysis demonstrated that the German electricity power demand could be met mainly by onshore wind and PV[2,3], with back-up supplied by 17% biogas electric power and 5% storage power. A subsequent project (KKW2) is studying the performance of renewable sources across the entire German grid. This work confirms the technical feasibility of a fully renewable power supply with an 80% contribution of wind and PV power. In particular, it shows that the grid remains stable if all planned and additional extensions of the extra-high voltage grid are realized and if renewable generation, storage and backup power stations are combined intelligently with renewable gas[4].

Target values for the contribution of each source required in an all-renewable power-supply scenario in Germany were also identified (green horizontal lines in Fig. 1). We have chosen the onshore and offshore wind targets to be half the wind power capacity of KKW1, which did not differentiate between on- and offshore wind[2]. The temporal variations of electricity demand in Germany and the UK are similar, and the UK monthly wind resource is a better match to peak evening demand than in Germany[3]. Hence it is possible to adjust the German KKW targets to the UK situation (grey horizontal lines in Fig. 1). In contrast, such extrapolation cannot be done for regions like Italy and south-west USA, where the electricity demand differs significantly from Germany[3] (partly due to different requirements for air conditioning). Our aim is to demonstrate how quickly countries might achieve an all-renewable electricity supply with established technologies. Clearly there are many other renewable technologies being developed that will make it easier to achieve the overall target. We suggest COP21 recommends that all countries run real-time KKW1 projects to determine the appropriate mix of renewable supplies for their national and state grids.

Over the past three years the exponential increase in PV installations has slowed in Germany and Italy[5,6] (Fig. 1a). China, Japan and the USA are now vying to become world leaders; yet it is likely that Germany will remain first in terms of PV power generated per head of population for many years. As shown in Fig. 1a, the KKW1 target for PV in Germany will be reached by 2019 if power-plant installations keep the average fractional increase achieved

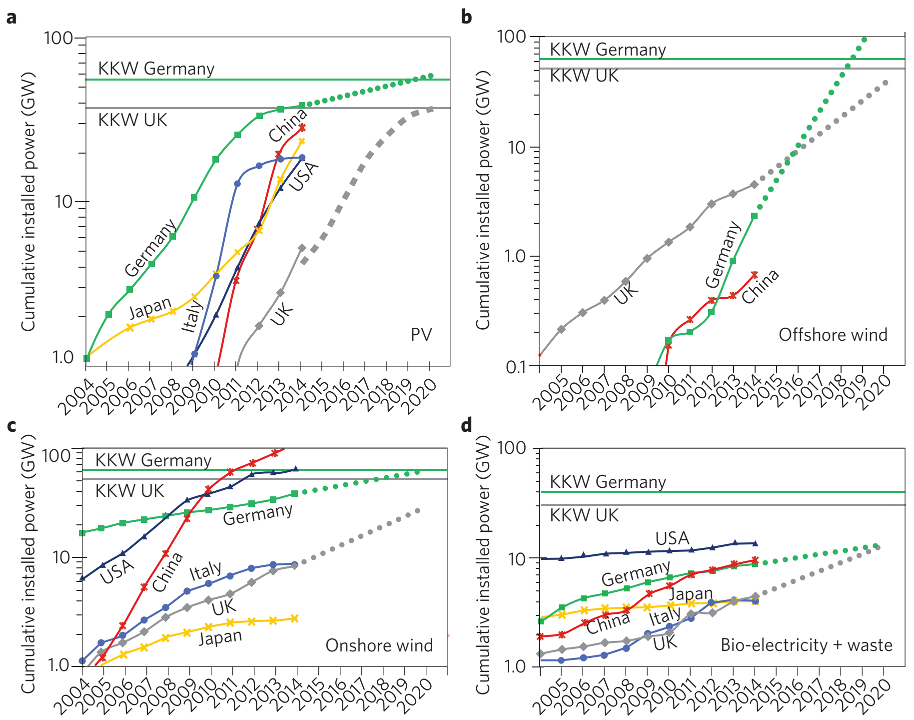

Figure 1 | Cumulative end-of-year installed renewable power for the countries indicated. Extrapolations assume the average fractional increase over the past ten years, except as described below. The all-renewable electricity targets for Germany and the UK are based on KKW1 (ref. 2), modified for the UK by differences in monthly supply and demand variation[3]. **a**, The German PV extrapolation assumes the average fractional increase over the past two years. The PV extrapolation for the UK is the actual increase achieved in Germany seven years earlier. **b**, The offshore wind extrapolation for Germany is based on the average fractional increase over the past four years. **c**, Onshore wind. **d**, Installed power for all forms of bio-electricity and waste. Extrapolations for Germany and the UK are both based on the average fractional increase over the past four years.

over the past two years (dotted green line). The dashed grey line in Fig. 1a shows that, if UK installations were to expand at the rate Germany achieved seven years earlier, PV would reach its target contribution for an all-renewable electricity supply by 2020. This is now unlikely, as the new government is proposing to cut PV subsidies severely[7]. The transition from a subsidized to a self-sustained PV market has been achieved in Italy, where the capacity for new installations has been dominated by small rooftop units since 2012[8].

Figure 1b compares the rate of expansion of offshore wind installations for China, Germany and the UK[9–11]. Offshore wind power installations in Italy, Japan and the USA are too small to appear on this graph. The steady, exponential rise in UK offshore wind installations over the past decade is impressive. If this expansion is maintained, UK offshore wind could achieve its target contribution to an all-renewable electricity supply by 2021. Germany will find it difficult to maintain a faster expansion than the UK, given their more restricted coastline. KKW2 assumed an offshore wind limit of 40 GW, with onshore wind taking a proportion of more than 50%[4]. The resource potential of onshore wind in Germany is high, and deployment could accelerate as the offshore installation rate starts to fall.

Figure 1c shows the onshore wind installations for the countries included in this study[9–11]. Although recent performance in the USA and in particular China is impressive, Germany still leads in terms of installed power per head of population. If the slower but steady exponential rise in Germany is continued, the KKW1 target should be achieved by 2020. If the trend of the past ten years continues, onshore wind power in the UK could reach the KKW1 target by 2022. However, government cuts[12] are likely to slow such increase, as has been happening in recent years in Italy[13].

Even if the rate of expansion slows, by 2020 PV, onshore wind and offshore wind in the UK could each far exceed the optimistic expectation of electric power generated by one new nuclear plant in 2023 (1.6 GW). New reactors would be unnecessary. It is also important to note that, in view of the German experience of high renewable power penetration on the grid[14], by 2023 the wholesale price of electricity will have fallen, so UK electricity consumers will then be paying an even bigger levy to cover the extra costs required to generate electricity from nuclear energy[15]. Analogous considerations apply to China where, in 2014, onshore wind power reached 115 GW and PV generated 28 GW (and is expected to reach 100 GW within a few years). Over the past two years, these two technologies have together expanded at ten times the rate of nuclear power, which was equal to 19 GW in 2014 (refs 16–18).

Comparisons of installed electrical power from all forms of bio and waste generation (Fig. 1d) should be treated with caution because the data include contributions from many different bioenergy technologies. In ref. 11, the US and Chinese contributions are described as solid biomass. On the other hand, half the UK contribution is described as plant biomass[9], and nearly half the German contribution is biogas[10]. From the data collected, we conclude that more government support is required in all countries to reach the KKW1 targets expected from bioenergy. In particular, we suggest new subsidies should stimulate the anaerobic digestion of farm and food waste in combined heat and power systems where the waste heat from electricity generation helps the production of biomethane. This approach does not conflict with land use for food and avoids the greenhouse gas emissions that would result if the waste were left to rot on farms or in landfill.

If the UK trends shown in Fig. 1a,c continue, PV power should be around 25 GW by 2018 and onshore wind above 29 GW by 2020. These are the levels Germany achieved in 2011 when the wholesale price of electricity started to fall[14]. In both countries the wholesale price of electricity is a larger proportion of the retail price for industrial consumers than for domestic ones. The recent cuts by the new UK government[7,12] will therefore deny British industry a future cost benefit that German industry should soon appreciate. Instead, redirecting the larger amounts of UK government tax-relief for natural gas[19] to replace the renewable levies on electricity consumers would be a more forward-looking strategy; in this way, the subsidies necessary to maintain the trends in Fig. 1 would not impact on retail prices.

An important consideration is the greenhouse gas emissions from electricity-generating technologies, which, according to the UK Committee on Climate Change, should be kept below the threshold of 50 g CO_2 per kWh by 2030[20]. Because the life-cycle emissions of all power plants that use renewable sources are already below this threshold[21], the results presented in Fig. 1 suggest that it would be practicable and safe to impose this environmental limit on all new electricity generators[1,3].

In conclusion, we recommend the following three-part policy for COP21: (1) an environmental life-cycle limit of 50 g CO_2 per kWh to be imposed on all new electricity-generating technology; (2) the transfer of fossil-fuel subsidies to renewables; and (3) KKW1 tests on national and state electricity grids to determine the most appropriate mix of renewable power from indigenous resources. Our evidence suggests that these three policies, taken together, will form the quickest, cheapest and safest approach to reduce carbon emissions from electricity generation. ❐

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