Could energy intensive industries be powered by carbon-free electricity?

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While the main thrust of the meeting on *Material efficiency: providing material services with less material production* was to explore ways in which society's net demand for materials could be reduced, this paper examines the possibility of converting industrial energy demand to electricity, and switching to clean electricity sources. This paper quantifies the scale of infrastructure required in the UK, focusing on wind and nuclear power as the clean electricity sources, and sets these requirements in the context of the decarbonization of the whole energy system using wind, biomass, solar power in deserts and nuclear options. The transition of industry to a clean low-carbon electricity supply, although technically possible with several different technologies, would have very significant infrastructure requirements.

Keywords: power per unit area; wind; nuclear; bioenergy

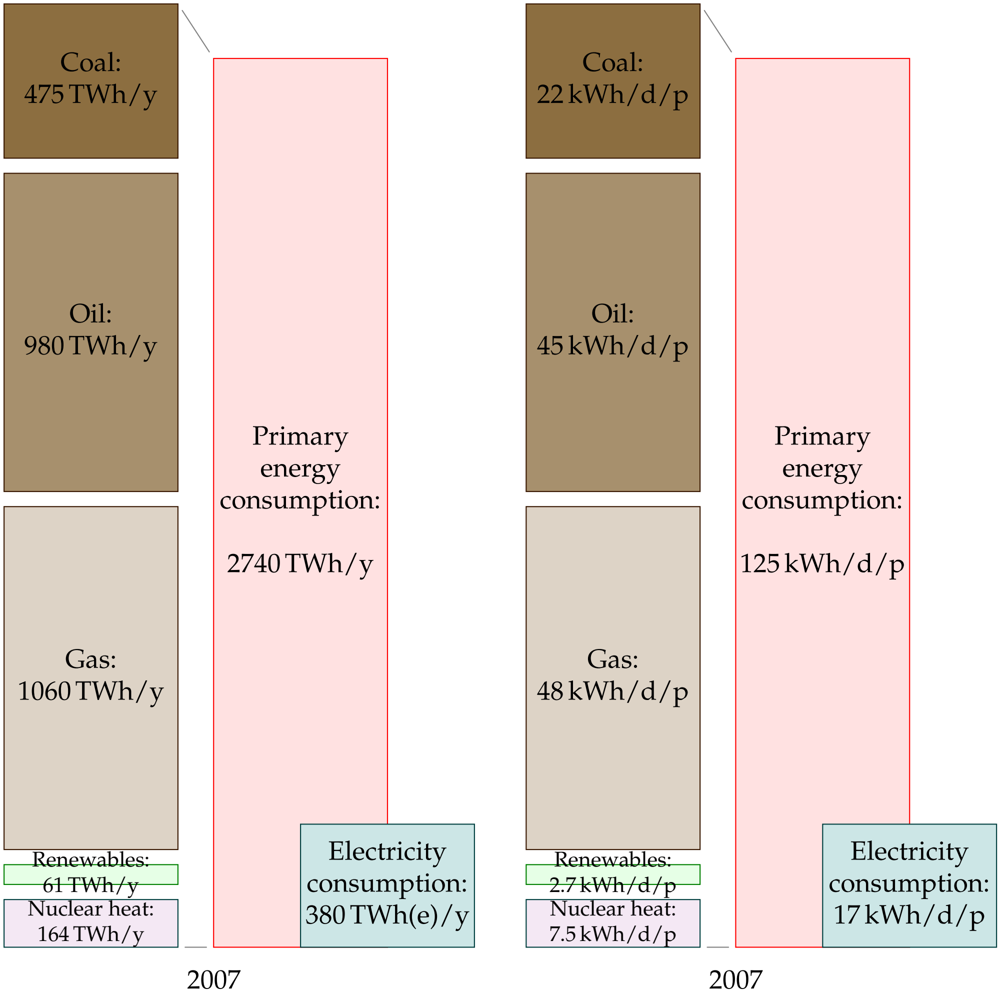
1. Overview

Industry accounts for roughly one third of the World's energy-consumption [Allwood and Cullen, 2011]; most of that energy today comes from coal, oil, and natural gas. What infrastructure would be required to deliver the same amount of energy from zero-carbon electricity? For a couple of possible power sources, I will compare the increase in infrastructure with existing systems, and describe the approximate land area required. (This simple-minded focus on energy neglects the fact that some of the fossil fuels used by industry deliver not only energy but also chemical services – for example, coal, converted to coke, acts as a reducing agent in blast furnaces.)

(*a*) *Useful units*

For concreteness, I will discuss *UK* industry, but to make the ideas easily transferrable to other countries, I will frequently express energy consumption and production rates in normalized, per-person units. Thus I will convert national energy consumption rates, which are sometimes expressed in gigawatts (GW) or terawatt-hours per year (TWh/y), into per-person units: kilowatt-hours per day per person (kWh/d/p). For the UK, with a population conveniently rounded to 60 million, a national power of 1 GW (per UK) is identical to 0.4 kWh/d/p, and 1 kWh/d/p is identical to 2.5 GW (per UK). For example, the UK's total primary energy consumption is roughly 310 GW, or 125 kWh/d/p, and the UK's average electricity consumption is roughly 42 GW, or 17 kWh/d/p.

Figure 1a shows the primary energy consumption of the UK, in 2007, broken down by energy source, and the electricity consumption in the conventional national



(a) (b)

Figure 1. UK primary energy consumption (a) in national units and (b) in per-capita units. Electricity production (which is derived from roughly one third of the primary consumption) is also shown.

units of terawatt-hours per year (1 GW $\simeq$ 9 TWh/y; 1 kWh/d/p $\simeq$ 22 TWh/y); and figure 1b shows the identical facts in per-capita units.

Whereas developed countries with different populations such as Germany, Denmark, and Switzerland have incomparable national power consumptions in gigawatts, many developed countries have quite similar per-capita energy consumptions. (Figure 2 shows on the vertical axis the per-capita consumptions of countries in 2005, and on the horizontal axis their population densities.)

So, I will focus on per-capita units; but to visualize the assets we are discussing we may sometimes wish to talk in national units. The following equivalence may

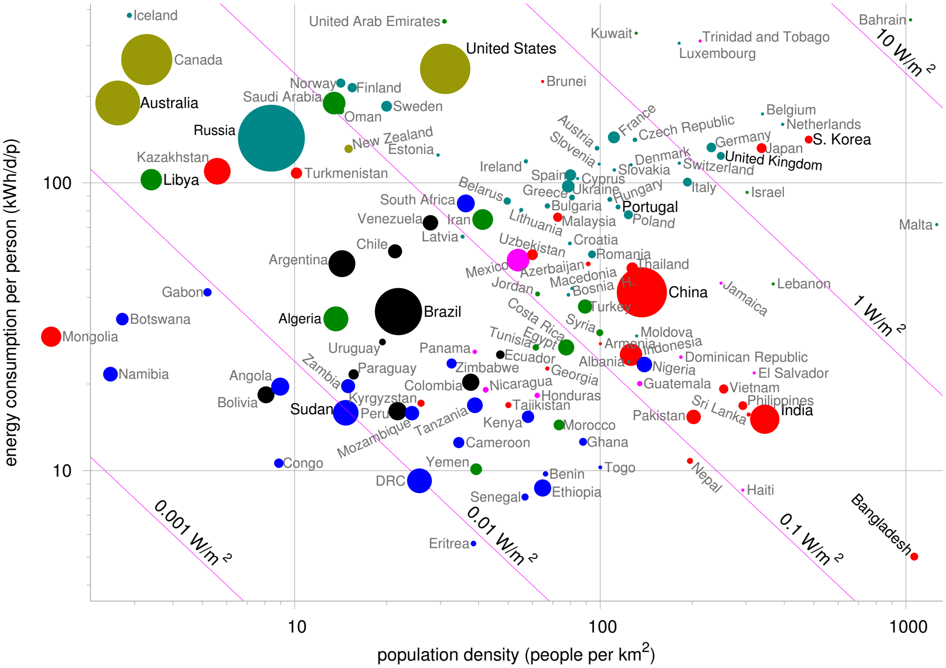


Figure 2. Power consumption per person versus population density, in 2005. Point size is proportional to land area, except for areas less than 38 000 km^2 (eg, Belgium), which are shown by a fixed smallest point size to ensure visibility. The straight lines with slope -1 are contours of equal power consumption per unit area. 78% of the world's population live in countries that have a power consumption per unit area greater than 0.1 W/m^2.

prove handy, especially for British audiences. All three of the following powers are equal (near enough) to **1 GW**:

1. The average electrical output of the **Sizewell B** nuclear power station (a standard pressurized water reactor with a maximum output of 1.19 GW);
2. The average electrical output of **all the UK's onshore wind turbines** during 2010 (these turbines were 2747 in number, and were grouped in roughly 273 windfarms whose area on a map is roughly 400 km^2; their nameplate capacity was 3.8 GW);
3. The energy consumption rate of **one blast furnace**, as measured by the heat of combustion of the coal it consumes. (One blast furnace consumes 5.8 Mt of coal per year and produces 2.5 Mt of steel per year, which would be enough to make the steel in the 2.5 million new cars per year that join the road in the UK; the UK has five such blast furnaces today.)

(In saying that these three quantities are 'equivalent', I am not necessarily asserting that the blast furnace could be powered by 1 GW of electricity instead of 5.8 Mt/y of coal; I'm simply pointing out that the three average rates of energy flow are identical.)

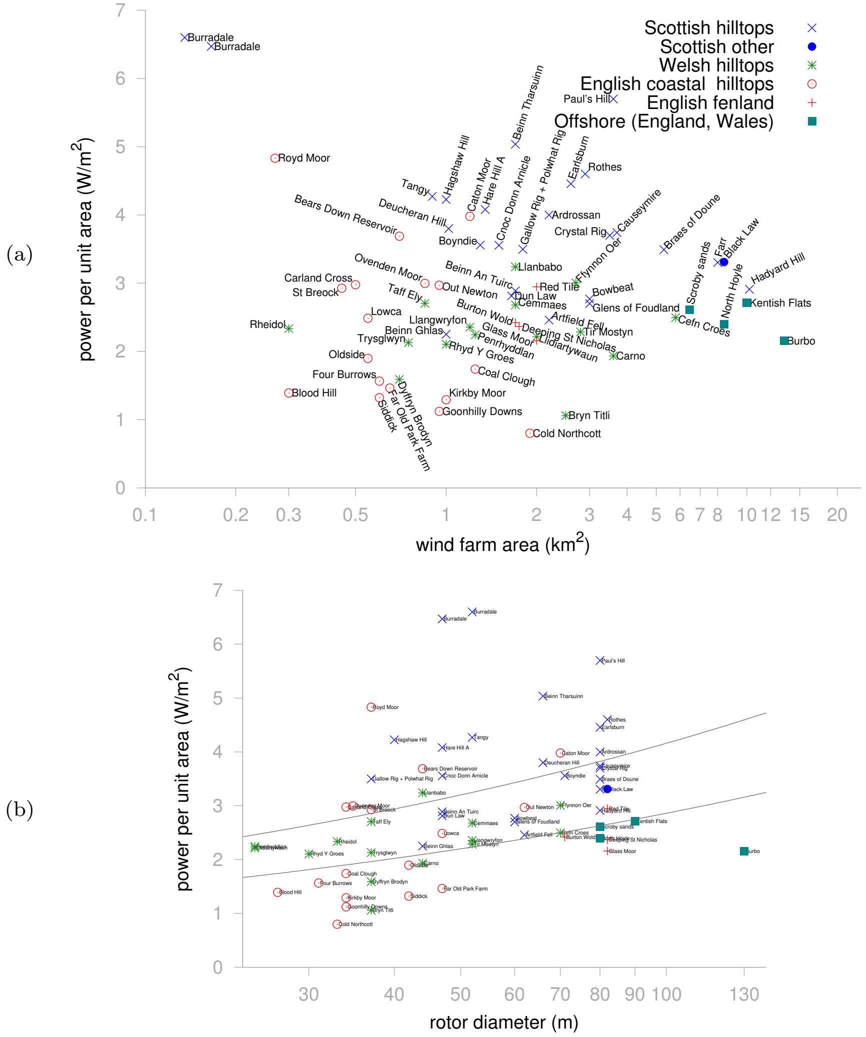


Figure 3. (a) Power per unit area of UK windfarms versus their size. The horizontal scale is logarithmic. (b) Power per unit area versus turbine diameter. The horizontal scale is logarithmic. The black curves in (b) show the trend that would be expected (within any single region) on the basis of the rule of thumb "doubling turbine size increases wind-speed by 10% and increases power by 30%", and assuming wind turbines' spacings are proportional to their diameters. See Appendix A for the methodology behind these data.

(*b*) *Power per unit area of wind and nuclear*

When visualizing future low-carbon electricity-generation options for the UK, two technologies with substantial technical potential are wind power and nuclear power. (Other technologies such as tidal power, waste-to-energy, deep geothermal power, and photovoltaics may also have useful technical potential, as discussed in MacKay [2008].)

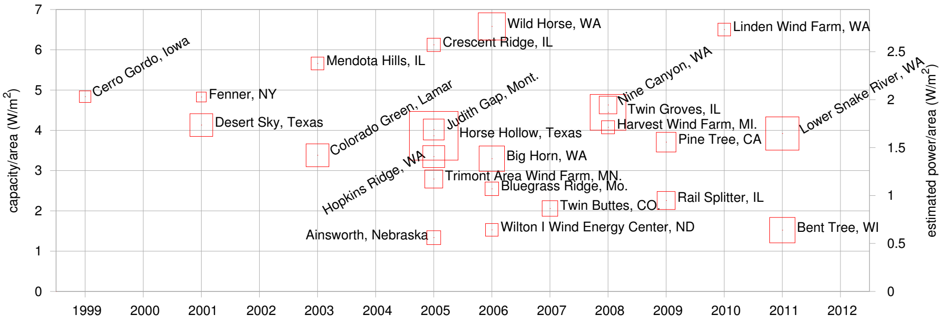


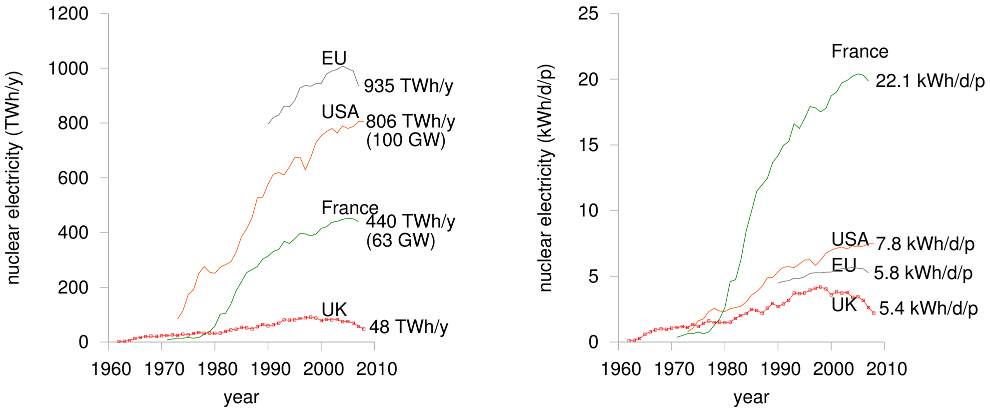
Figure 4. Capacity per unit area (left axis) and estimated power output per unit area (right axis) of US windfarms versus commissioning date. For the right axis, a load factor of 42% is assumed. Point area is proportional to capacity; the largest farm shown, Horse Hollow, has a capacity of 735 MW. According to Gallman [2011], Horse Hollow has an average power per unit area of 1.55 W/m^2.

The power per unit area of most large wind farms in the UK is between 1.5 W/m^2 and 4.5 W/m^2 (figure 3). Of course, the productivity of wind farms depends on their location; some English farms produce less than 2.5 W/m^2, and most Scottish farms produce more – perhaps 3.5–4 W/m^2; the four offshore wind farms in figure 3 all deliver about 2.5 W/m^2. The power production per unit area of most large wind farms in the USA is between 0.7 W/m^2 and 2.5 W/m^2 (figure 4), and there is no obvious trend in the data indicating that power per unit area is increasing with time. In the calculations that follow, I estimate the land required for wind farms assuming a typical power per unit area of 2.5 W/m^2.

The power production per unit area of nuclear power stations is roughly 1000–2000 W/m^2 when the facility is running. Taking into account the time during which the land lies unavailable during decommissioning, and the land associated with waste storage and reprocessing, Appendix B shows that the aggregate power per unit area of the first generation of nuclear power facilities in the UK is roughly 140 W/m^2.

2. The energy demand of industry

From the Digest of UK Energy Statistics [MacLeay et al., 2011], 18 kWh per day per person (44 GW) is going into industry. (This quantity is a final energy consumption, not a primary energy consumption. In arriving at this quantity, I've included blast furnaces, but excluded the energy consumption of oil, gas and coal extraction, and of petroleum refineries.) Of that energy demand, electricity is already being used by industry to the tune of 5.2 kWh/d/p, so the non-electrical demand amounts to 12.5 kWh/d/p, which is 31 GW per UK. To put that in context, today's total electricity consumption in the UK is 17 kWh/d/p. So as a rough ball-park estimate, if you wanted to electrify industry without making any change to its efficiency, then you would need to nearly double electricity production. (I've assumed here a one-for-one substitution of coal, gas, and petroleum by electricity; that is, 1 kWh of chemical energy substituted by 1 kWh of electricity.) Moreover, to make the 5.2 kWh/d/p of



(a) (b)

Figure 5. Electricity generated from nuclear fission versus time in a few regions, in national units (a) and per-capita units (b).

existing electrical supply to industry all low-carbon, assuming that 75% of it is not low-carbon today, another 4 kWh/d/p of low-carbon electricity would be needed (10 GW per UK). So, in total, to decarbonize industry in this way we would need to supply new low-carbon electricity of 16 or 17 kWh/d/p – roughly 40 GW per UK.

3. Some ways to supply low-carbon electricity

Is this possible? Yes. Referring back to section 1a, we can deliver an extra 40 GW by adding an extra 40 Sizewell-Bs or an extra 40 replicas of the UK onshore wind fleet of 2010, or any mix of those two actions. (I call wind and nuclear power "low-carbon" rather than zero-carbon to reflect the small quantity of greenhouse-gas emissions that are embodied in the construction and maintenance of the infrastructure.)

40 Sizewell-Bs would be four times the UK's current nuclear fleet, which is technically achievable – France, for example, built more than 50 GW in a couple of decades (figure 5). In per-capita terms, France and Sweden are both countries that produce more than 16 kWh per day per person (figure 6). The land area for 40 GW of nuclear power stations and their support facilities would be about 290 km^2, if the nuclear industry's use of land continued in line with the first generation of nuclear power facilities in the UK. 290 km^2 is about one tenth of one percent of the UK's land area, and is equal, for example, to the sum of the areas of the Balmoral and Sandringham estates.

The pure-wind option would involve roughly 130 GW of offshore wind capacity or 150 GW of onshore wind capacity (assuming load factors of 31% and 27% respectively). The area of sea or land required for the windfarms would be about 16 000 km^2, which is 6.5% of the UK's land area, or 77% of a Wales; the wind capacity divided by the area of the UK would be roughly 0.57 W/m^2 – about six times higher than the capacity-to-land-area ratio of Denmark (figure 7a). The pure-wind option would imply that the wind capacity per person was about 2200–2500 W,

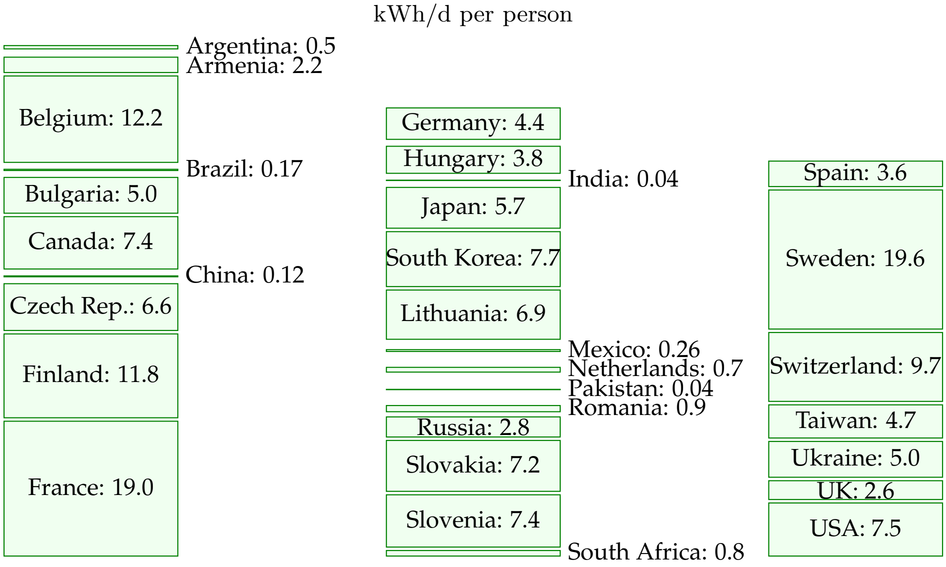


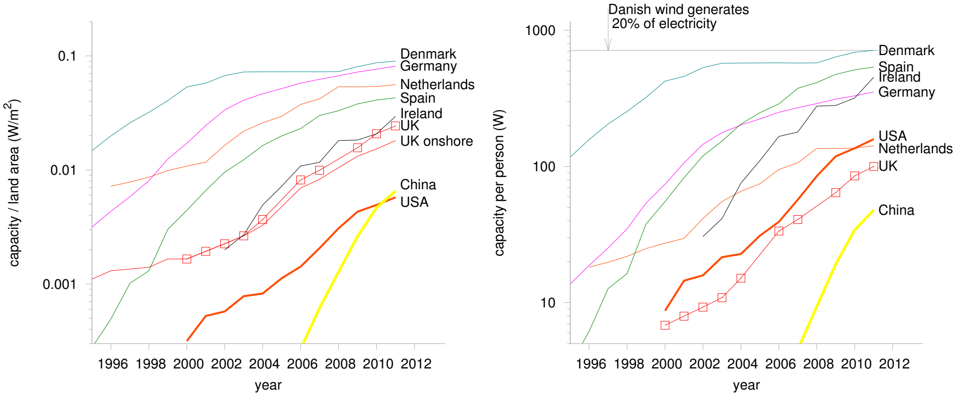
Figure 6. Electricity generated per capita from nuclear fission in 2007, in kWh per day per person, in each of the countries with nuclear power.

which is about 3 times that of Denmark (700 W, see figure 7b). So a wind-only mix delivering 16 kWh/d/p would tread where no country has gone before in terms of wind-exploitation.

If one opted for a wind-dominated solution then electricity-balancing services would be needed to deal with the intermittency of the wind: either interconnectors to countries willing to receive and export many tens of gigawatts, or methods for moving equally large quantities of demand in time, or methods for storing extremely large amounts of electricity. To make up for a missing 40 GW for just a single windless day using storage would require about 1000 GWh of storage per UK (16 kWh per person) which is one hundred times the energy-storage capacity of Dinorwig or Cruachan, the two largest pumped storage facilities in the UK; and nationwide near-windless periods of *four* days are not uncommon.

4. Context and caveats

While asserting that both the four-fold growth in nuclear power and the forty-fold increase in wind power over 2010 levels are technically possible, I am conscious that neither of these developments would be judged easy by politicians or engineers. The social, political and engineering challenges are all the greater when we embed the task of decarbonizing industry within the overall goal of decarbonizing society. In the UK, at least two thirds of our energy consumption is non-industrial – the biggest sectors are transport, space-heating in buildings, and non-industrial electricity consumption. The total energy consumption of the UK, remember, is 125 kWh per day per person. Even with radical improvements in energy efficiency, the UK will need several times the 16 kWh/d/p we have discussed thus far.



(a) (b)

Figure 7. (a) Wind capacity per area, and (b) wind capacity per person, for several countries. Both vertical axes have logarithmic scales. (Note that to estimate the average power *generation* from this wind capacity one must multiply by the load factor; load factors for wind range from about 20% in Germany to 42% in the biggest farms in the USA.)

Figure 8 shows, to scale, on a map of the UK, four ways of delivering 16 kWh per day per person. The map shows by grey squares, 100 km^2 each, the area of the wind farms discussed in the previous section, and it shows by purple dots sufficient sites for nuclear power stations to deliver 40 GW, assuming roughly two Sizewell Bs per site. The map also shows by green polygons, some in the UK, some elsewhere, the area of land (80 000 km^2) required to create 16 kWh/d/p of bioenergy, assuming a net power per unit area of 0.5 W/m^2. Each of the three large green squares is 22 588 km^2 in size, which is the area of New Jersey, and just a shade larger than the area of Wales. And the map shows the area required in someone else's desert (2700 km^2) to deliver 16 kWh/d/p from concentrating solar power, assuming a power per unit area of 16.5 W/m^2, and allowing for losses of 10% between the Sahara and Surrey. If that power were delivered by overhead high-voltage DC power-lines in a strip of land 750 m wide and 1600 km long, the land area occupied in Spain and France by the power-lines would be about 1200 km^2.

These four technologies are not the only low-carbon power sources, though they are among the most promising sources with large potential. All the other renewable sources share the property of wind power that they are relatively diffuse: they deliver a power per unit area in the ballpark of wind's 2.5 W/m^2. Solar parks, for example, which are sprouting up across Europe, deliver an average power per unit land area of roughly 4 W/m^2 [MacKay, 2012]; and hydroelectric facilities in Scotland deliver about 11 W per square metre of lake area, and about 0.2 W per square metre of catchment area [MacKay, 2008]. So whatever the mix of renewables one develops, the land area or sea area required for 16 kWh/d/p is roughly as indicated by the area of the wind farms. When I talk of the land "required", of course not all the area is literally used up. In a wind farm for example, only a tiny fraction of the land area is occupied by turbines, foundations, and access roads. The rest remains available for agriculture or other uses.

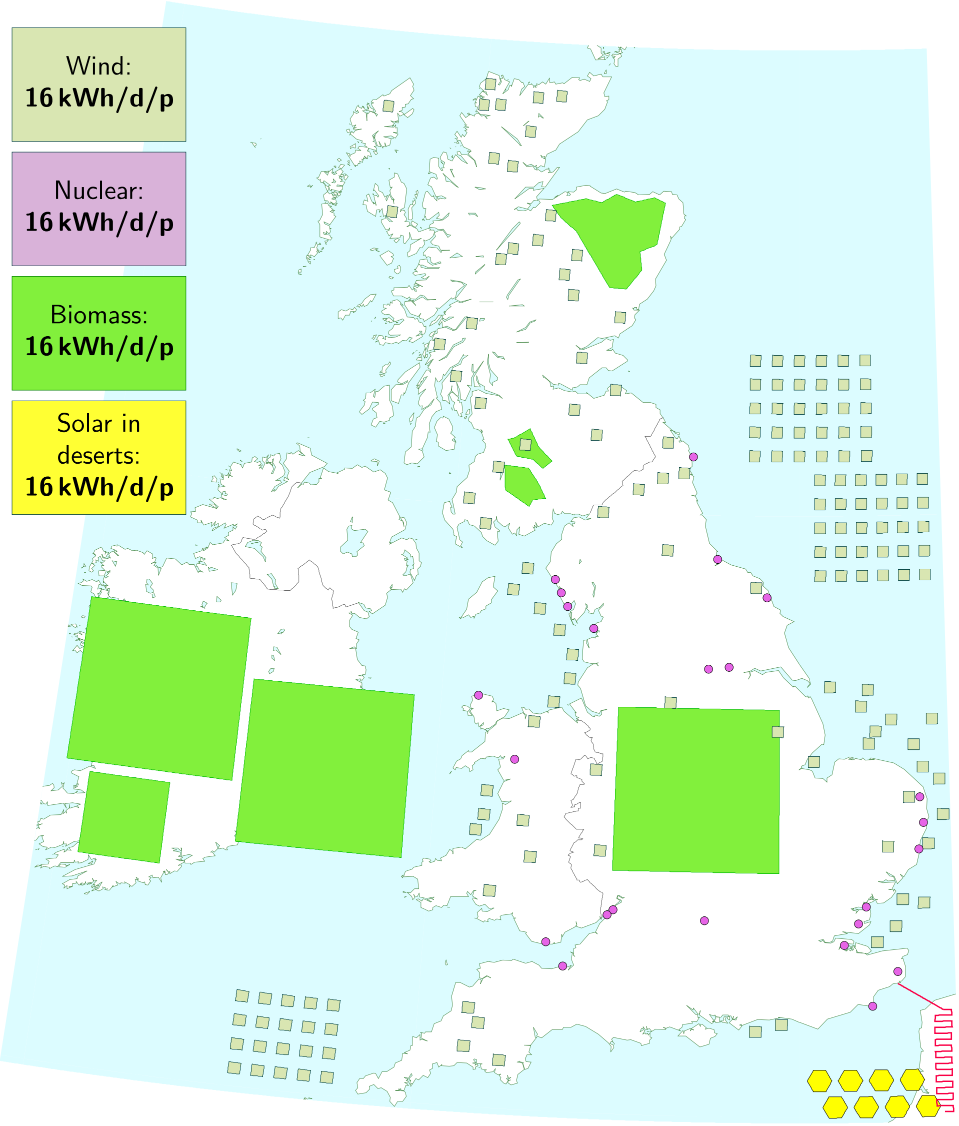


Figure 8. Four ways of delivering 16 kWh/d per person in the UK.

(*a*) *Public discussion of decarbonization pathways*

I have emphasized the area required for energy infrastructure, but this is of course not the only important metric. Cost, resilience, and air quality are other metrics that may be important in the public deliberation of energy options. The UK Department of Energy and Climate Change has published an interactive open-source tool, the 2050 Pathways Calculator, which allows the user to explore the effectiveness for the UK of different combinations of demand-side and supply-side actions, and which computes and displays several metrics. The UK government's *Carbon Plan*, published in December 2011 [Department of Energy and Climate

Figure 9. Red Tile wind farm, East Anglia, and its associated land area. The blue grid's spacing is 1 km. Each turbine has a diameter of 82 m and a capacity of 2 MW. Map © Crown copyright; Ordnance Survey.

Change, 2011], illustrates the magnitude of effort required to achieve the UK's 2050 goal of 80% decarbonization within its own borders. The *Carbon Plan* sketches a corridor of pathways in which: per-capita demand in the UK falls by between 31% and 54%; nuclear power generation capacity increases from today's 10 GW to between 16 GW and 75 GW; renewable electricity-generation capacity increases from today's 10 GW to between 22 GW and 106 GW; carbon capture and storage electrical capacity increases to between 2 GW and 40 GW; and bioenergy use increases from today's 73 TWh/y to between 180 and 470 TWh/y (21–54 GW).

The authors of the 2050 Pathways Calculator would be delighted to see enhancements made to the Calculator's industry module.

(*b*) *This paper hasn't described how to decarbonize industry*

This paper has only explored the scale of energy infrastructure required to provide a low-carbon flow of (electrical) energy equal to the current high-carbon flow of (mainly chemical) energy into industry. I have not addressed the questions of whether the energy-consuming industrial processes could in fact be electrified, nor what their efficiencies would be when electrified. Moreover, some industrial processes *directly* emit carbon dioxide because of chemistry, as well as indirectly from their energy consumption – cement production is the most notable example – and this paper has not addressed the challenge of eliminating these chemically-driven emissions.

Acknowledgements

I thank Emma Devenport and Katharine Hill for assistance with the production and quality assurance of the data in figures 3 and 4.

Appendix A. Power per unit area of wind farms

Methodology for figure 3: from the monthly statistics published at `https://www.renewablesandchp.ofgem.gov.uk/` and collated by Renewable Energy Foundation [2009], whole-year average outputs were obtained for each wind farm; areas of wind farms were measured by the author from Ordnance Survey maps, which showed the locations of turbines, as illustrated in figure 9. For isolated turbines, the "area" was deemed to be a circle of diameter five times the turbine diameter. For a large farm, the perimeter of the "area" was sketched allowing a strip around the turbines of width equal to half that farm's typical turbine spacing, or 2.5 turbine diameters, whichever was the larger. Figure 9 shows Red Tile wind farm, which is typical of the British farms represented in figure 3.

Appendix B. Power per unit area of nuclear facilities

Table 3 shows the energy produced by several nuclear facilities in the UK, and their land areas. The average power per unit area of each site is calculated in two ways: first, during operation alone, and second, taking into account the duration of decommissioning. The more modern sites in table 3 generated about $2000\,\mathrm{W/m^2}$ when operating, or about $500\,\mathrm{W/m^2}$ on average if we take account of the time taken for decommissioning; the aggregate power density of all these sites, including Sellafield (the largest site, which has hosted other nuclear functions beside power generation), is $140\,\mathrm{W/m^2}$.

Nuclear power also has a footprint where the ore is mined, but this footprint is shared with the mining of other useful minerals. The Olympic Dam Mine in South Australia, opened in 1988, produces much of the world's uranium oxide, along with significant quantities of copper, silver, and gold. The site has an area of about $20\,\mathrm{km^2}$ and is expected to be able to sustain production of roughly 4000 tonnes of uranium oxide per year for 200 years. If the uranium oxide is used in once-through reactors with an efficiency of 1 GW-year per 191 t, the uranium-related power production per unit area of the mine is roughly $1000\,\mathrm{W/m^2}$. If the uranium oxide were used in 60-fold more efficient breeder reactors, the power per unit area would be $63\,000\,\mathrm{W/m^2}$.

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Scotland	average power (MW)	area (km^2)	power/ area (W/m^2)	turbine diameter (m)	load factor (%)	years averaged
Ardrossan	8.83	2.2	4.0	80	29.4	2005–07
Artfield Fell	5.41	2.2	2.5	62	27.7	2006–07
Beinn An Tuirc	4.91	1.7	2.9	47	32.7	2003–07
Beinn Ghlas	2.25	1	2.25	44	26.8	2003–07
Beinn Tharsuinn	8.6	1.7	5.0	66	28.8	2006–11
Bowbeat	8.31	3	2.8	60	27.0	2004–07
Boyndie	4.6	1.3	3.6	71	28.4	2007–12
Braes of Doune	18.5	5.3	3.5	80	25.7	2008–11
Burradale	1.07	0.17	6.5	47	50	2003–07
Burradale	0.89	0.14	6.6	52	50	2004–07
Causeymire	13.8	3.7	3.7	80	28.6	2005–07
Cnoc Donn Arnicle	5.33	1.5	3.6	47	35.5	2003–07
Crystal Rig	13	3.5	3.7	80	26	2005–07
Deucheran Hill	3.9	1.02	3.8	66	24	2003–07
Dun Law	4.64	1.65	2.8	47	27	2004–07
Earlsburn	11.6	2.6	4.5	80	30.9	2008–12
Farr	26.4	8	3.3	80	28.7	2007–12
Gallow Rig & Polwhat Rig	6.34	1.8	3.5	37	29.3	2003–08
Glens of Foudland	8	3	2.7	60	29	2006–07
Hadyard Hill	29.7	10.2	2.9	80	24.8	2006–12
Hagshaw Hill	4.22	1	4.2	40	27.5	2003–08
Hare Hill A	5.51	1.35	4.1	47	41.7	2003–08
Paul's Hill	21.7	3.6	6.0	80	33.8	2007–08
Rothes	13.3	2.9	4.6	82	26.2	2006–07
Tangy	3.36	0.9	4.3	52	30.0	2003–08
Black Law	30.0	8.4	3.6	82	24.2	2007–08

Wales	average power (MW)	area (km^2)	power/ area (W/m^2)	turbine diameter (m)	load factor (%)	
Bryn Titli	2.65	2.5	1.1	37	26.8	2002–11
Carno	7.0	3.6	1.9	44	20.7	2003–08
Cefn Croes	14.5	5.8	2.5	70	32.2	2006–08
Cemmaes	4.56	1.7	2.7	52	29.8	2003–08
Dyffryn Brodyn	1.11	0.7	1.6	37	20.2	2003–08
Ffynnon Oer	8.1	2.7	3.0	70	25.4	2007–08
Llanbobo	5.51	1.7	3.2	44	27.0	2003–08
Llangwryfon	2.83	1.2	2.4	52	30.2	2004–06
Llidiartywaun	4.43	2	2.2	25	23.4	2003–08
Penrhyddlan	2.81	1.25	2.2	25	21.7	2003–08
Rheidol	0.70	0.3	2.3	33	29.2	2003–08
Rhyd Y Groes	2.10	1	2.1	30	29.2	2003–08
Taff Ely	2.30	0.85	2.7	37	25.5	2003–08
Tir Mostyn	6.4	2.8	2.3	52	29.8	2006–08
Trysglwyn	1.60	0.75	2.1	37	28.5	2003–08

Table 1. *Power per unit area of major onshore wind farms in Scotland and Wales.*

England (on hilltops or near coast)	average power (MW)	area (km^2)	power/ area (W/m^2)	turbine diameter (m)	load factor (%)	years averaged
Bears Down Reservoir	2.58	0.7	3.7	44	26.9	2003–08
Blood Hill	0.42	0.3	1.4	27	18.6	2003–08
Carland Cross	1.49	0.5	3.0	34	24.8	2002–12
Caton Moor	4.8	1.2	4.0	70	30.0	2007–12
Coal Clough	2.2	1.25	1.74	34	22.7	2002–12
Cold Northcott	1.52	1.9	0.80	33	22.4	2002–12
Far Old Park Farm	0.95	0.65	1.46	47	20.6	2002–12
Four Burrows	0.94	0.6	1.57	31	20.9	2002–11
Goonhilly Downs	1.07	0.95	1.12	34	19.0	2002–10
Kirkby Moor	1.29	1	1.29	34	26.9	2002–12
Lowca	1.37	0.55	2.5	47	29.6	2002–12
Siddick	0.79	0.6	1.3	42	18.9	2002–11
Oldside	1.04	0.55	1.9	42	19.3	2002–11
Out Newton	2.83	0.95	3.0	62	31.0	2002–12
Ovenden Moor	2.55	0.85	3.0	34.8	27.7	2002–11
Royd Moor	1.30	0.27	4.8	37	20.1	2002–11
St Breock	1.32	0.45	2.9	37	26.3	2002–07

England (other)	average power (MW)	area (km^2)	power/ area (W/m^2)	turbine diameter (m)	load factor (%)	
Burton Wold	4.11	1.7	2.4	71	20.6	2006–12
Deeping St Nicholas	4.14	1.75	2.4	82	25.9	2007–12
Glass Moor	4.3	2	2.2	82	27.0	2006–12
Red Tile	5.9	2	2.9	82	24.5	2007–12

Offshore	average power (MW)	area (km^2)	power/ area (W/m^2)	turbine diameter (m)	load factor (%)	
Burbo	28.7	13.3	2.2	130	31.9	2008–11
Kentish Flats	27.1	10.0	2.7	90	30.1	2006–12
North Hoyle	20.2	8.4	2.4	80	33.6	2005–11
Scroby sands	16.8	6.45	2.6	80	28.1	2005–11

Table 2. *Power per unit area of major onshore wind farms in England and offshore. Sources: powers and diameters –* `https://www.renewablesandchp.ofgem.gov.uk/`*; areas – measured by the author from Ordnance Survey maps.*

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Site	Power per unit area		Area	Generation		
	during generation W/m^2	allowing for decommissioning W/m^2	km^2	energy delivered TWh	start–end	End of decommissioning
Sellafield*	47	14	2.76	54	1956–2003	2120
Chapelcross	158	52	0.96	60	1959–2004	2095
Berkeley	673	155	0.27	43	1962–1989	2079
Bradwell	856	263	0.2	60	1962–2002	2092
Hunterston A	1730	375	0.15	57	1964–1989	2080
Dungeness A	1670	519	0.2	120	1965–2006	2097
Hinkley Point A	1770	496	0.19	103	1965–2000	2090
Trawsfynydd	2110	464	0.15	72	1965–1991	2083
Sizewell A	2240	679	0.14	110	1966–2006	2098
Oldbury	616	208	0.51	124	1967–2012	2101
Wylfa	2910	919	0.21	220	1971–2012	2101
Aggregate	470	140	5.74	1023		

Table 3. *Power per unit area of some UK nuclear power-generating facilities, sorted by the start-year of generation. * The Sellafield site includes Calder Hall and Windscale, which served not only civilian power generation but also military functions. Source: Nuclear Decommissioning Authority Business Plan 2012–2015.* `www.nda.gov.uk`

Energy Foundation, 21 John Adam Street London WC2N 6JG, November 2009. Also `http://www.ref.org.uk/roc-generators/`.