Solar energy in the context of energy use, energy transportation, and energy storage

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Contribution to Discussion Meeting 'Can solar power deliver?'.

Taking the United Kingdom as a case study, this paper describes current energy use and a range of sustainable energy options for the future, including solar power and other renewables. I focus on the the area involved in collecting, converting, and delivering sustainable energy, looking in particular detail at the potential role of solar power.

Britain consumes energy at a rate of about 5000 watts per person, and its population density is about 250 people per square kilometre. If we multiply the per-capita energy consumption by the population density, we obtain the average primary energy consumption per unit area, which for Britain is 1.25 watts per square metre. This areal power density is uncomfortably similar to the average power density that could be supplied by many renewables: the gravitational potential energy of rainfall in Scottish highlands has a raw power per unit area of roughly 0.24 watts per square metre; energy crops in Europe deliver about 0.5 watts per square metre; wind farms deliver roughly 2.5 watts per square metre; solar photovoltaic farms in Bavaria and Vermont deliver 4 watts per square metre; in sunnier locations, solar photovoltaic farms can deliver 10 watts per square metre; concentrating solar power stations in deserts might deliver 20 watts per square metre. In a decarbonized world that is renewable-powered, the land area required to maintain today's British energy consumption would have to be similar to the area of Britain. Several other high-density, high-consuming countries are in the same boat as Britain, and many other countries are rushing to join us. Decarbonizing such countries will only be possible through some combination of the following options: the embracing of country-sized renewable power generation facilities; large-scale energy imports from country-sized renewable facilities in other countries; population reduction; radical efficiency improvements and lifestyle changes; and the growth of non-renewable low-carbon sources, namely "clean" coal, "clean" gas, and nuclear power.

If solar is to play a large role in the future energy system, we need new methods for energy storage; very-large-scale solar would either need to be combined with electricity stores, or it would need to serve a large flexible demand for energy that effectively stores useful energy in the form of chemicals, heat, or cold.

Keywords: power; area; renewable energy; population density; electricity storage; concentrating solar power

1. Introduction

The enormous technical potential of solar power is often pointed out. Eicke Weber, director of the Fraunhofer Institute for Solar Energy Systems, puts it like this: "The total power consumption of the humans on Earth is approximately 16 terawatts. In the year 2020 it is expected to grow to 20 terawatts. The sunshine falling on the Earth is 120 000 terawatts. From this perspective, energy from the sun is virtually unlimited."† While these physical numbers are correct, we must also take note of the variation of solar intensity with location and with time. Thanks to geometry and clouds, the average intensity of sunshine in London is less than half the intensity in Los Angeles (figure 1a). At European latitudes, the average intensity of sunshine varies significantly with the time of year: the average intensity on a horizontal surface in London or Edinburgh is nine times smaller in winter than in summer (figure 1b). Meanwhile, energy demand in the UK is significantly larger in winter than summer (figure 2). Moreover, in the UK, daily electricity demand has its maximum not at noon but at 6pm. So, rather than simply comparing the average total global sunshine with average total human energy demand, this paper will compare *local* solar intensity with *local* energy-demand *in the locations where the humans live*. We should also take into account the realistic efficiency of solar conversion technologies. When these important details are considered, we will find that, in many human-dense locations, the realistic potential of sunshine is only a little larger, on average, than current consumption. To envisage solar making a dominant contribution to energy demand in such locations, we must therefore think carefully about how to store or transport energy from times and places with more plentiful sunshine.

2. Average power consumption per unit area

Figure 3 shows a map of the world in which the horizontal axis is a country's population density, and the vertical axis is its energy consumption per person, in kWh per day per person. (1 kWh per day is approximately 40 W; "energy consumption" here is total primary energy consumption, including solid, liquid, and gaseous fuels for electricity, transport, heating, and industry.) The area of each point in figure 3 is proportional to the area of that country. Both axes are logarithmic; countries to the right have population densities more than one-hundred-fold greater than countries to the left, and countries at the top consume roughly one-hundred times more, per capita, than countries at the bottom.

The points in figure 3 show data for 2005, but the world does not stand still. Figure 4 indicates, by line segments, 15 years of "progress" for Australia, Libya, the United States, Sudan, Brazil, Portugal, China, India, Bangladesh, the United Kingdom, and South Korea. For many countries, between 1990 and 2005, population densities increased and per-capita energy consumption increased. So there is a general trend for countries to move up and to the right, towards the top right corner, where we already find countries such as the United Kingdom, Germany, and Japan. Figure 5 gives a longer view of this trend over the last few centuries.

† National Geographic magazine `http://ngm.nationalgeographic.com/print/2009/09/solar/johnson-text`

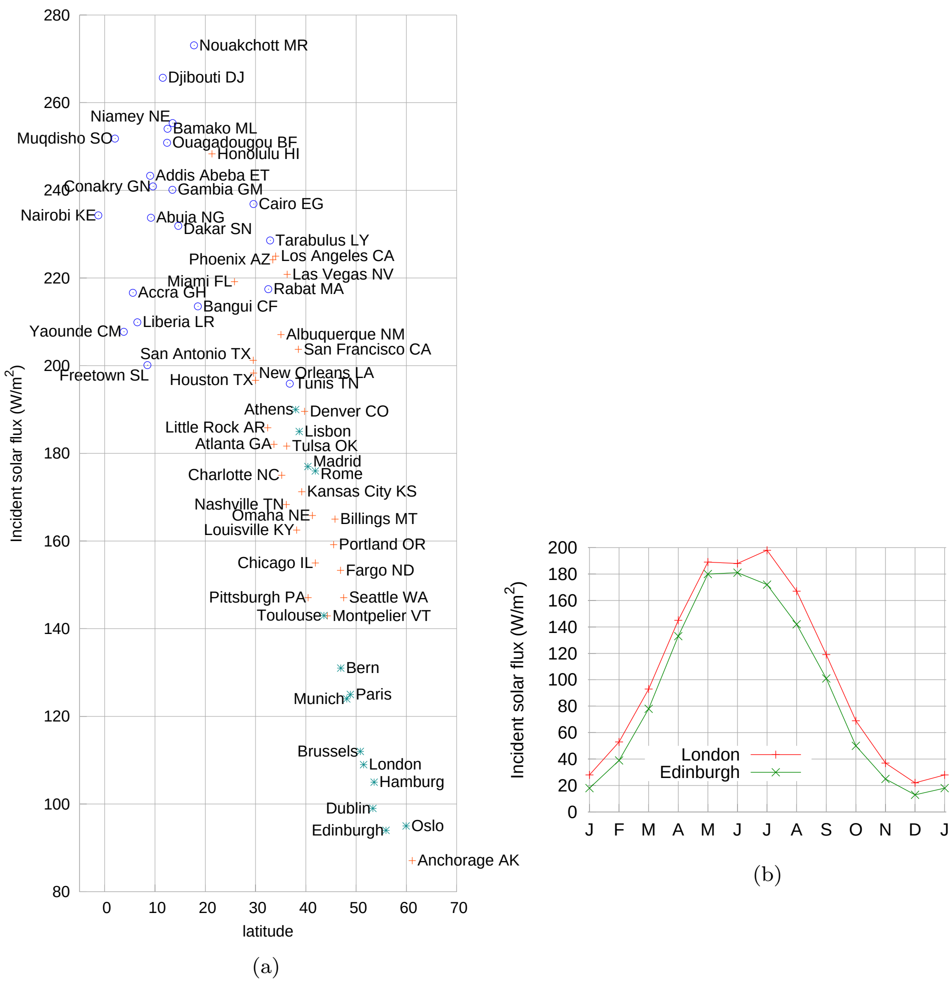

Figure 1. Variation of average sunshine with latitude and with time of year. (a) Average power of sunshine falling on a horizontal surface in selected locations in Europe, North America, and Africa. These averages are whole-year averages over day and night. (b) Average solar intensity in London and Edinburgh as a function of time of year. (Average powers per unit area are sometimes measured in other units, for example kWh per year per square metre; for the reader who prefers those units, the following equivalence may be useful: 1 W = 8.766 kWh per year.) Sources: NASA "Surface meteorology and Solar Energy" `eosweb.larc.nasa.gov`; `www.africanenergy.com/files/File/Tools/AfricaInsolationTable.pdf`; `www.solarpanelsplus.com/solar-insolation-levels/`; `lightbucket.wordpress.com/2008/02/24/insolation-and-a-solar-panels-true-power-output/`.

Now, if we multiply a country's per-capita energy consumption by its population density, we obtain the country's average energy consumption per unit area. Contours of equal energy consumption per unit area in figures 3–5 are straight lines with slope −1. For example, Saudi Arabia and Norway (towards the top left of

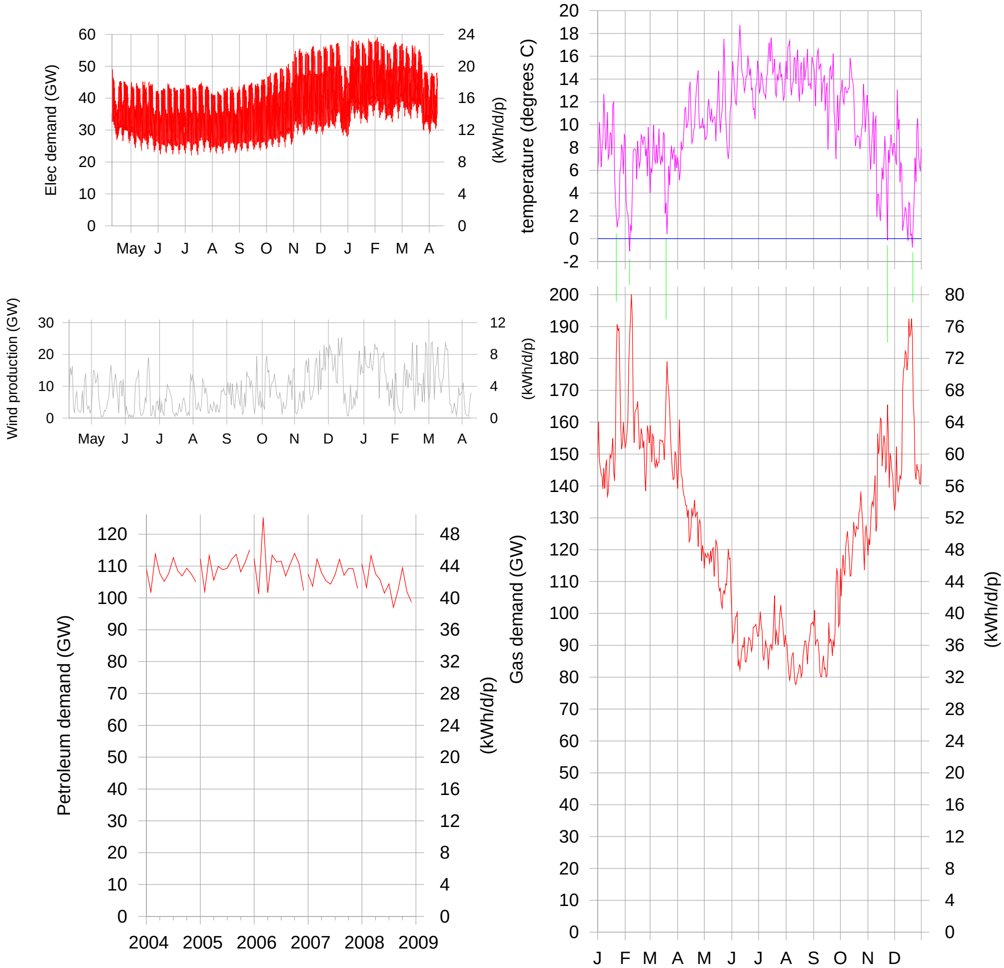

Figure 2. Electricity, gas, and transport demand; and modelled wind production, assuming 33 GW of capacity, all on the same vertical scale. Wind production is modelled by scaling data from Ireland.

figure 3), Mexico (in the middle), and Guatamala and Haiti (towards the bottom right) all consume about $0.1\,\mathrm{W/m^2}$. While $0.1\,\mathrm{W/m^2}$ is the world's average power consumption per unit area, 78% of the world's population live in countries that have a power consumption per unit area greater than $0.1\,\mathrm{W/m^2}$. (Much as, in a town with some crowded buses and many empty buses, the average number of passengers per bus may be small, but the vast majority of passengers find themselves on crowded buses.) Britain and Germany, for example, in the top right of figure 3, have an energy consumption per unit area of $1.25\,\mathrm{W/m^2}$.

This areal power density is uncomfortably similar to the average power density that could be supplied by many renewables: the gravitational potential energy of all rainfall in Scottish highlands has a raw power per unit area of roughly $0.24\,\mathrm{W/m^2}$; energy crops in Europe deliver about $0.5\,\mathrm{W/m^2}$; onshore and offshore wind farms in England and Wales deliver roughly $2.5\,\mathrm{W/m^2}$; wind farms on Scottish hilltops

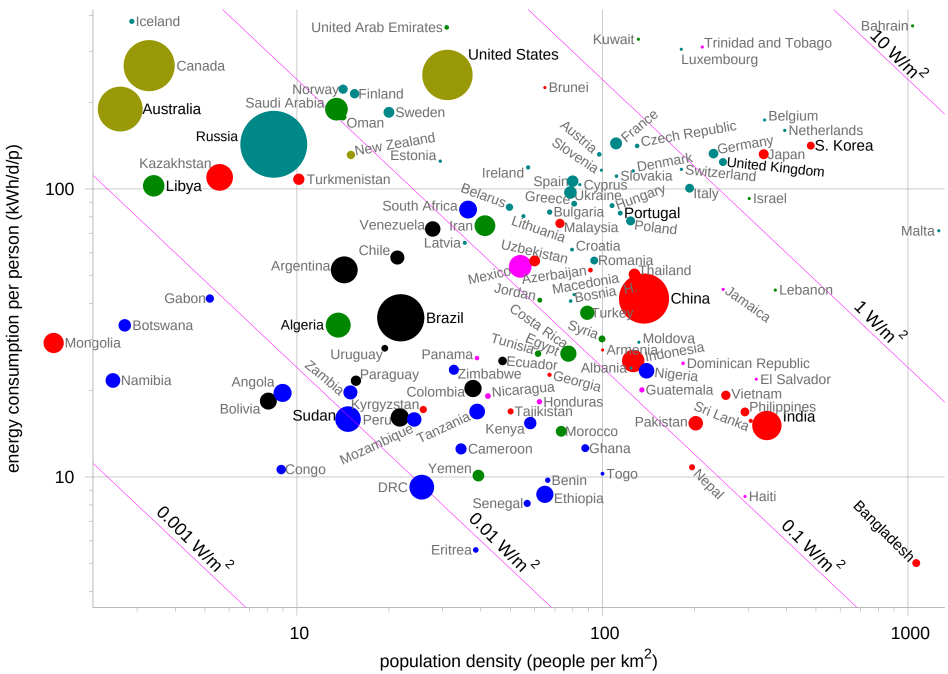

Figure 3. Power consumption per person versus population density, in 2005. Point size is proportional to land area (except for areas less than 38 000 km^2 (eg, Belgium), which are shown by a fixed smallest point size to ensure visibility). The straight lines with slope -1 are contours of equal power 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. (Average powers per unit area are sometimes measured in other units, for example kWh per year per square metre; for the reader who prefers those units, the following equivalence may be useful: 1 W = 8.766 kWh per year.)

deliver roughly 3.5 W/m^2 [MacKay, 2013]; as we will see in the following section, solar photovoltaic farms in Northern Europe deliver 4–5 W/m^2 and even in sunnier locations few solar photovoltaic farms deliver more than 10 W/m^2; concentrating solar power stations in deserts might deliver 20 W/m^2 [MacKay, 2008, p. 184]. Figure 6 shows some of these renewable power densities by green contour lines, along with the country data from figure 3. Solar farms produce less power per unit area than individual solar panels because the filling factor – the ratio of functional-panel-area to land-area – is small, say, 14%. The same goes for concentrating solar power stations: The Solúcar PS10 solar tower has a mirror-to-land-area ratio of 14%.) In principle, some of these renewable power densities might be increased by technological progress – for example Dabiri [2011] calculates that closely-packed vertical-axis wind turbines might produce roughly 18 W/m^2 – but this prediction has yet to be verified in a real-world demonstration at megawatt scale; Dabiri's small experiments on a six-turbine 7.2-kW array demonstrated daily mean power densities ranging from 2.1 to 10.5 W/m^2 [here I have scaled the results (6–30 W/m^2) reported by Dabiri [2011] by the ratio of the convex hull of the six turbines (48.6 m^2) to the area of the six squares (138.24 m^2) they would occupy in a larger square-

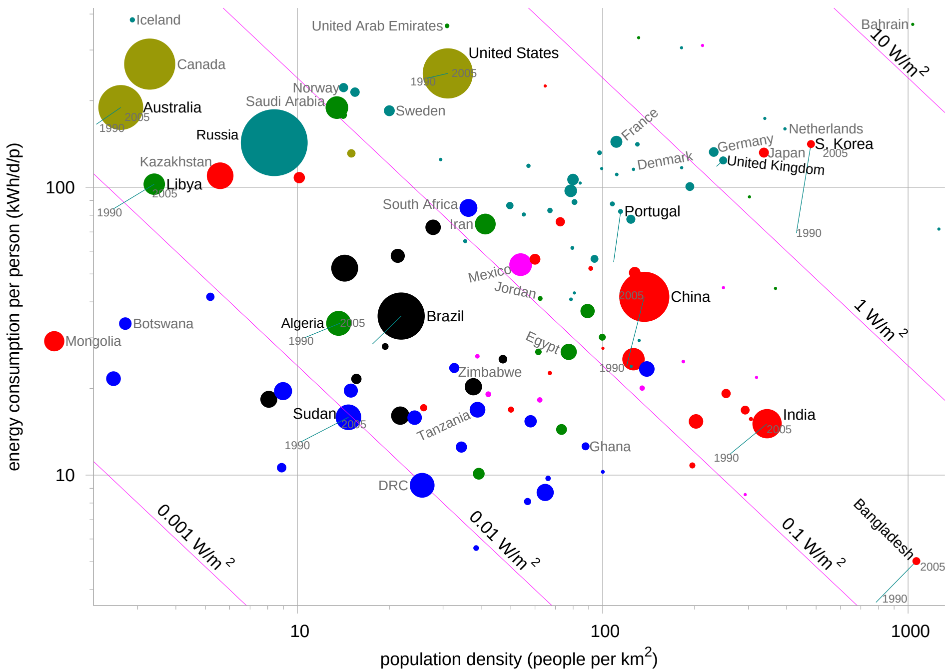

Figure 4. Power consumption per person versus population density, in 2005. Point size is proportional to land area. Line segments show 15 years of "progress" (from 1990 to 2005) for Australia, Libya, the United States, Sudan, Brazil, Portugal, China, India, Bangladesh, the United Kingdom, and S. Korea. 78% of the world's population live in countries that have a power consumption per unit area greater than 0.1 W/m^2.

lattice array]; and the capital cost per MWh of the turbines would probably be significantly greater than that of standard horizontal-axis turbines. Nevertheless, I acknowledge that future cost-competitive wind technologies *may* achieve powers per unit area twice as big as those I have described here; the airborne wind turbine being developed by Makani Power (originally described by Loyd [1980]) seems a promising way to deliver such improvements at low cost. Similarly, I acknowledge it might be possible (with triple-junction technology, say) to make solar modules that are twice as efficient as today's single-junction devices, which can't perform beyond the Shockley–Queisser limit [Hopfield and Gollub, 1978]; but realists might argue that widespread deployment of cost-effective photovoltaics is more likely to involve *cheaper* thin-film solar cells such as amorphous silicon, dye-sensitized cells, or organics [Friend, 2009], which would deliver *lower* powers per unit land area than 5–20 W/m^2.

The energy generation and transmission systems with which we are familiar have much higher power densities. The Pembroke oil refinery, for example, processes 220 000 barrels of crude oil per day (16 GW) and has an area of 4 km^2 – a rough power per unit area of 4000 W/m^2. The Longannet power station (2.4 GW capacity) occupies 1.6 km^2, including all the land associated with the Longannet coal mine; its average power output is about 1.2 GW, which implies a power per unit area

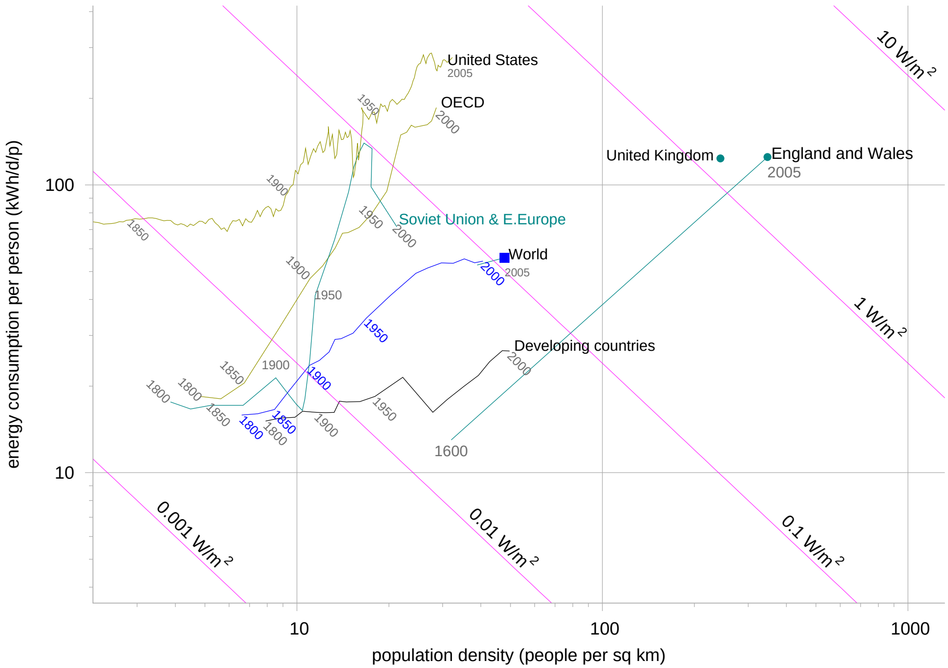

Figure 5. Power consumption per person versus population density, from 1600 or 1800 to 2005. OECD = Organization for Economic Cooperation and Development. Sources: [Grubler, 2008, Wrigley, 2010].

of 740 $\mathrm{W/m^2}$. Nuclear power facilities have a similar power per unit area to coal [MacKay, 2013]. The most diffuse component of today's familiar energy system is the network of electrical transmission lines. The land area 'occupied' by the UK's high-voltage transmission system is somewhere between 230 $\mathrm{km^2}$ and 1300 $\mathrm{km^2}$ (a route length of about 13 000 km, multiplied by a 'width of land occupied' of between 18 m and 100 m, depending whether one defines the land 'occupied' to be the land directly under the wires, or the wider strip of land whose uses are constrained by the high-voltage lines). So the power per unit area of a coal-fired electricity generation and transmission system in the UK, using Longannet as a representative generator, and scaling its area up to the national electricity consumption (42 GW), would be in the range $(42\,\mathrm{GW})/(57\,\mathrm{km^2} + 230{\leftrightarrow}1300\,\mathrm{km^2}) = 146{\leftrightarrow}31\,\mathrm{W/m^2}$.

Figure 6 shows that, in a world that is renewable-powered, the land area required to maintain today's British energy consumption would have to be similar to the area of Britain. The same goes for Germany, Japan, South Korea, Belgium, and the Netherlands. Decarbonizing such high-density, high-consuming countries will only be possible through some combination of the following options: the embracing of local, near-country-sized renewable power generation facilities; large-scale energy imports from equally large renewable facilities in other countries; population reduction; radical increases in energy efficiency (see Jochem et al. [2002] and Jochem [2004] for discussion of the research and development challenges of delivering a 66% reduction in per-capita energy consumption in a European country); lifestyle

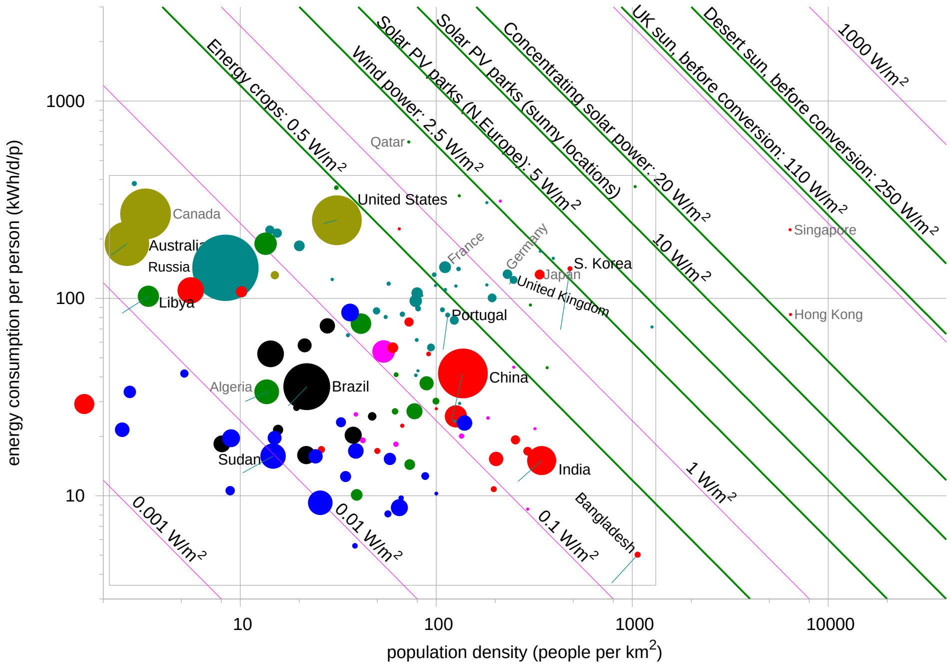

Figure 6. Power consumption per person versus population density, in 2005. Point size is proportional to land area. The diagonal lines are contours of power-consumption-per-unit-area. The grey box corresponds to the region shown in figures 3 and 4.

changes that save energy; and the growth of non-renewable low-carbon sources, namely 'clean coal', 'clean gas', and nuclear power. (By 'clean' coal and gas, I mean fossil-fuel use with carbon capture and storage; carbon capture and storage enables continued fossil fuel use with much lower carbon emissions.)

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. The UK government's *Carbon Plan*, published in December 2011, illustrates the magnitude of effort required to achieve the UK's 2050 goal of 80% decarbonization. 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).

3. The power per unit area of solar farms

All Earth Renewables `www.allearthrenewables.com`, a Vermont-based company, provide detailed production data for their photovoltaic installations. The largest solar farm in Vermont, site 316, has 382 sun-tracking modules, with a combined

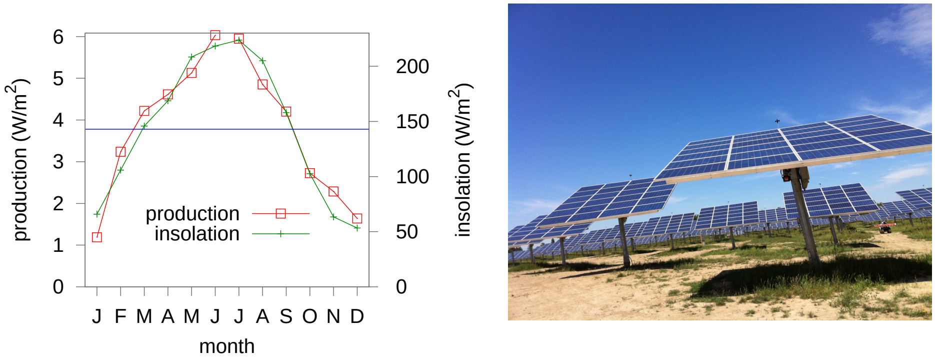

Figure 7. Electricity production from AllEarth Renewables Solar Farm, 350 Dubois Drive, South Burlington, Vermont (latitude 44°26' N), during the last 6 months of 2011 and the first 6 months of 2012; and insolation (10-year average) for Montpelier (33 miles away from the farm) from the NASA Surface meteorology and Solar Energy Data Set. Photo courtesy of AllEarth Renewables.

peak capacity of 2.1 MW. The farm's land-area is 0.1 km^2. Figure 7 shows this farm's electricity production during its first 12 months of operation, expressed as a power per unit area, and the 10-year average insolation for Montpelier, a nearby location. The ratio of vertical scales for production and insolation, set by least-squares regression, is 0.0268:1, from which we can estimate that the average annual insolation (143 W/m^2) will lead to average production of 3.8 W/m^2. This overall conversion efficiency of 2.68% is presumably the product of a solar module efficiency of about 19% (including DC-to-AC conversion losses) and a filling factor (functional-panel-area to land-area ratio) of about 14%. This Vermont solar farm is composed of two-axis sun-tracking modules; alternative farm designs using single-axis sun-tracking panels or fixed panels have similar power per unit area: the 10.1-MW (peak) Solarpark in Bavaria occupies about 30.6 hectares at three sites (17.4 ha at Mühlhausen, 7.5 ha at Günching, and 5.7 ha at Minihof), and was expected, when built, to deliver 217 GWh over 20 years (1.24 MW on average), which is a power per unit area of 4.0 W/m^2 [SolarServer, 2005]; the 2.8-MW Hohenberg/Marktleugast farm occupies 7.36 ha and has a predicted production of 2.6 GWh per year, which is a power per unit area of 4.0 W/m^2 [Clear Energy, 2010]. These facilities were built when solar electricity was paid handsome tariffs (45¢ per kWh); if land area were valued more highly relative to renewable power then no doubt a reoptimized solar farm could have higher power per unit area, but the maximum possible in locations such as Vermont (incoming power 143 W/m^2), Munich (124 W/m^2), and Edinburgh (94 W/m^2) would be 23 W/m^2, 20 W/m^2, and 15 W/m^2, respectively, if we assume a module efficiency of 20% and a filling factor of 80%.

Figures 8–10 and tables 1–2 contain data from the above three solar farms, and from several more solar photovoltaic farms around the world, both roof-mounted and ground-mounted, some with single-axis sun-tracking and some composed of fixed structures. Figure 8 and table 3 also include data from some thermal solar electric facilities in Spain. (Any individual item in this data-set should be treated with caution since it was not possible to quality-assure every farm's land-area and energy-production.) Figure 8 shows the solar farms' average power per unit land-

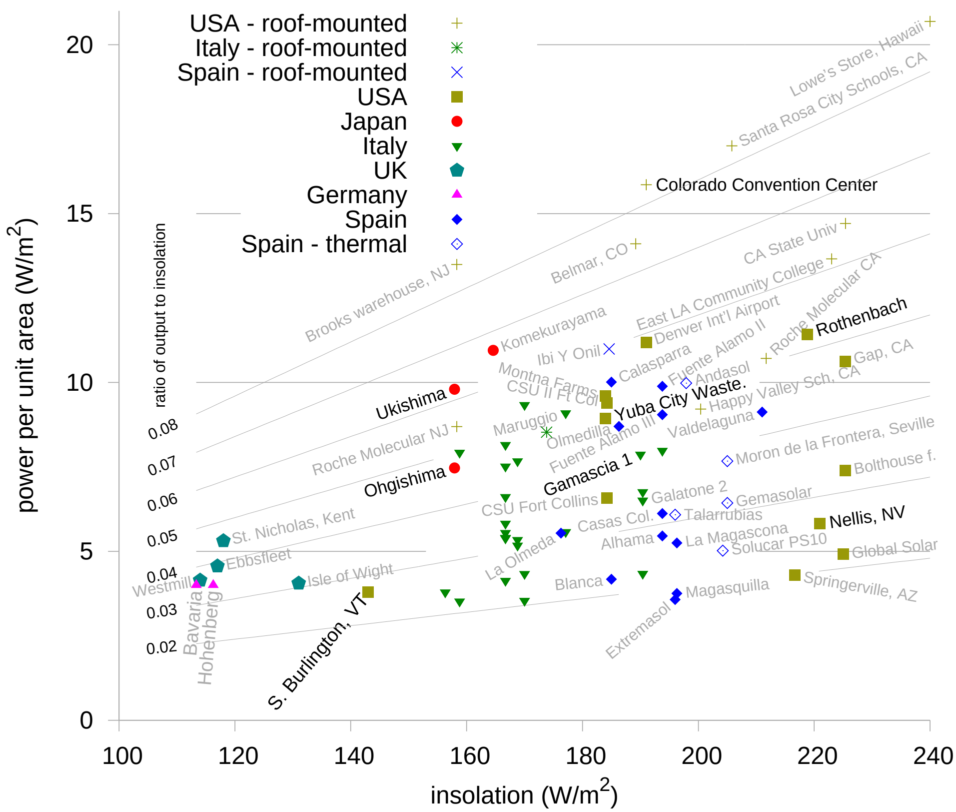

Figure 8. Solar farms' average power per unit land-area versus the local insolation (ie, average incident solar flux per unit of horizontal land area). Filled triangles, squares, circles, and pentagons show ground-based solar photovoltaic farms. The other point styles indicate roof-mounted photovoltaic farms and solar thermal facilities. Where the solar farm name is shown in black, actual electricity-production data has been displayed; otherwise, for names in grey, the electricity production is a predicted value. (See tables 1–3 for data.) Both axes show average power per unit area, averaging over the whole year including day and night. (Average powers per unit area are sometimes measured in other units, for example kWh per year per square metre; for the reader who prefers those units, the following equivalence may be useful: 1 W = 8.766 kWh per year.)

area versus the local insolation (ie, average incident solar flux per unit of horizontal land area). This figure conveys several interesting facts. First, for almost all ground-based solar farms (shown by the filled circles and polygons), the ratio of the output power per unit land area to the incoming solar power per unit land area is between 0.02 and 0.06. Second, all four farms in the UK and both farms in Germany have power per unit area between 4.0 and 5.3 W/m^2. Third, in Italy and Spain, where the average insolation is between 47% and 86% greater, the power per unit area of every ground-based solar farm is between 3.5 W/m^2 and 10 W/m^2. Fourth, in all

name	insolation (W/m^2)	capacity (MW)	area (ha)	production (GWh/y)	power /area (W/m^2)	load factor (percent)
Germany: photovoltaics						
Bavaria solarpark$^{(1)}$	113.3	10.1	30.6	10.85	4.0	12.3
Hohenberg/Marktleugast$^{(0)}$	116.3	2.8	7.36	2.6	4.0	10.6
Japan: photovoltaics						
Ukishima$^{(0)}$	151	7	11	**9.45***	9.80	15.4
Ohgishima$^{(0)}$	158	13	23	**15.06***	7.47	13.2
Komekurayama$^{(0)}$	164	10	12.5	12.0	10.95	13.7
USA: photovoltaics						
South Burlington, Vermont$^{(2)}$	143	2.1	10.0	**3.44***	3.8	18.7
Belmar, CO$^{+(1)}$	189.2	1.75	1.86	2.30	14.11	15.0
Bolthouse farms$^{(1)}$	225.4	1.85	6.48	4.20	7.39	25.9
Brooks warehouse, NJ$^{+(0)}$	158.3	0.60	0.57	0.67	13.49	12.8
CA State Univ$^{+(0)}$	225.4	1.17	1.21	1.56	14.71	15.2
Colorado Conv. Cen.$^{+(1)}$	191	0.30	0.28	**0.39***	15.85	14.8
CSU Fort Collins$^{(1)}$	184.2	2.00	6.07	3.50	6.58	20.0
CSU II Fort Collins$^{(0)}$	184.2	3.30	6.07	5.00	9.40	17.3
Denver Int'l Airport$^{(1)}$	191	2.00	3.06	3.00	11.18	17.1
East LA Community College$^{+(0)}$	223	1.19	1.22	1.46	13.66	14.0
Gap, CA$^{(1)}$	225.4	1.06	2.04	1.90	10.62	20.4
Global Solar, AZ$^{(0)}$	225	0.77	2.89	1.25	4.92	18.5
Happy Valley Sch, CA$^{+(0)}$	200.4	0.25	0.46	0.37	9.21	17.0
Lowe's Store, Hawaii$^{+(0)}$	240	0.39	0.33	0.60	20.69	17.5
Montna Farms, CA$^{(1)}$	184	0.39	0.86	0.72	9.60	21.2
Nellis, NV$^{(1)}$	221	14.02	56.7	**28.91***	5.82	23.5
Roche Molecular CA$^{+(0)}$	211.7	0.20	0.28	0.26	10.72	15.0
Roche Molecular NJ$^{+(0)}$	158.3	0.91	1.30	0.99	8.69	12.4
Rothenbach, FL$^{(0)}$	218.8	0.25	0.26	**0.26***	11.43	11.8
Santa Rosa City Schools, CA^{+}	205.8	0.83	0.79	1.18	17.00	16.2
Springerville, AZ$^{(0)}$	216.7	6.48	25.9	9.75	4.29	17.2
Yuba City Wastewater, CA$^{(1)}$	184	0.84	2.30	**1.80***	8.93	24.4

Table 1. *Predicted or actual electricity production by solar photovoltaic farms in various countries, versus their electrical capacity and the land area occupied.* $^{+}$ *denotes roof-mounted installations.* $^{(0)}$ *denotes fixed structure (not sun-tracking);* $^{(1)}$ *denotes a single-axis solar tracking system;* $^{(2)}$ *denotes a two-axis solar tracker. "Insolation" is the average power per unit of horizontal area in the vicinity of the farm, from* `eosweb.larc.nasa.gov`*, based on 22 years' data. (Average powers per unit area are sometimes measured in other units, for example kWh per year per square metre or kWh per day per square metre; for the reader who prefers those units, the following equivalences may be useful: 100 W = 876.6 kWh per year = 2.4 kWh per day.) Production data that is labelled* * *denotes* actual *production; otherwise the production stated is a published* estimate. *These data are shown graphically in figures 8, 9, 10, and 14.*

name	insolation (W/m^2)	capacity (MW)	area (ha)	production (GWh/y)	power /area (W/m^2)	load factor (percent)
Italy: photovoltaics						
Anagni FRa$^{(0)}$	170	6.56	11.30	9.25	9.34	16.1
Anagni FRb$^{(0)}$	170	6.98	32.1	9.98	3.54	16.3
Bluway$^{(0)}$	158.8	0.37	1.70	0.53	3.52	16.0
Cantore$^{(0)}$	168.8	9.31	19.00	12.78	7.67	15.7
Capri$^{(0)}$	177.1	3.00	9.00	4.40	5.58	16.7
Cassino$^{(0)}$	170	3.99	14.60	5.55	4.34	15.9
Ceal$^{(0)}$	158.8	0.99	2.00	1.39	7.93	16.0
Depuratore SGR$^{(0)}$	166.7	0.10	0.20	0.14	8.16	16.4
Fiumicino$^{(0)}$	193.8	9.85	20.00	14.00	7.99	16.2
Follerato 1$^{(0)}$	168.8	0.99	3.30	1.50	5.18	17.3
Galatone 1$^{(0)}$	190.4	0.95	3.96	1.51	4.34	18.1
Galatone 2$^{(0)}$	190.4	0.99	2.80	1.60	6.51	18.4
Gamascia 1$^{(0)}$	190	9.69	23.00	**15.86***	7.87	18.7
Maruggio$^{(0)}$	177.1	0.99	2.00	1.59	9.10	18.4
Ruffano$^{(0)}$	190.4	0.95	2.54	1.50	6.76	18.1
Geosis 1$^{(0)}$	166.7	0.99	3.00	1.46	5.55	16.8
Geosis 2$^{(0)}$	166.7	0.99	4.00	1.45	4.14	16.6
Marinella$^{(0)}$	168.8	4.38	12.90	6.04	5.34	15.7
Minervino^{+}	173.8	3.96	8.00	5.98	8.53	17.2
Posta Piana$^{(0)}$	166.7	1.00	2.80	1.43	5.83	16.3
Posta Conca$^{(0)}$	166.7	1.00	2.50	1.45	6.62	16.6
San Severo$^{(0)}$	166.7	1.98	6.10	2.89	5.40	16.6
Servigliano$^{(0)}$	156.3	0.99	4.00	1.33	3.79	15.3
Siponto$^{(0)}$	166.7	0.96	2.90	1.37	5.39	16.3
Torremaggiore$^{(0)}$	166.7	1.00	2.20	1.45	7.52	16.6
UK: photovoltaics						
Ebbsfleet$^{(0)}$	117	4.90	12.50	5.00	4.56	11.6
Isle of Wight$^{(0)}$	131	4.50	13.50	4.80	4.06	12.2
St. Nicholas, Kent$^{(0)}$	118	0.60	1.17	0.54	5.31	10.4
Westmill, Watchfield$^{(0)}$	114	5.00	12.14	4.41	4.14	10.1

Table 2. *Predicted or actual electricity production by solar photovoltaic farms in Italy and the UK, versus their electrical capacity and the land area occupied. See table 1 for explanation.*

locations in the USA with insolation above 160 W/m^2, the power per unit area of every ground-based farm is between 4.3 W/m^2 and 11.4 W/m^2.

Figure 9 explores a financially important attribute of a solar farm, namely the load factor, that is, the ratio of its average electrical output to its capacity. Capacity is expensive, so to get a good return on investment one desires a big load factor. The solar farms in Germany and the UK have the lowest load factors of all (roughly 10%–12%). There is a fairly strong correlation between insolation and load factor; in the sunniest locations, load factors around 20% are common, and almost all the

name	insolation (W/m^2)	capacity (MW)	area (ha)	production (GWh/y)	power /area (W/m^2)	load factor (percent)
Spain: photovoltaics						
Alhama$^{(0)}$	193.8	6.34	21.00	10.04	5.46	18.1
Blanca$^{(0)}$	185	6.96	23.90	8.74	4.17	14.3
Calasparra$^{(0)}$	185	13.30	26.8	23.52	10.01	20.2
Casas Coloradas$^{(0)}$	193.8	7.02	20.50	11.00	6.12	17.9
Extremasol$^{(0)}$	196	11.52	65.8	20.62	3.57	20.4
Fuente Álamo II$^{(0)}$	193.8	8.87	18.20	15.78	9.89	20.3
Fuente Álamo III$^{(0)}$	193.8	10.31	22.40	17.76	9.05	19.7
La Magascona$^{(1)}$	196.3	23.04	100.0	46.00	5.25	22.8
La Olmeda$^{(0)}$	176.3	6.00	18.00	8.74	5.54	16.6
Magasquilla$^{(1)}$	196.3	11.52	70.0	23.04	3.75	22.8
Olmedilla$^{(0)}$	186.3	11.52	25.00	19.07	8.70	18.9
Ibi Y Onil$^{+(0)}$	184.6	2.63	5.50	5.30	10.99	23.0
Valdelaguna$^{(0)}$	211	10.93	20.00	16.00	9.13	16.7
Spain: thermal solar electricity						
Morón de la Frontera, Seville$^{(1)}$	205	50.0	273.6	184.00	7.67	42.0
Talarrubias, Badajoz$^{(1)}$	196	50.0	344.9	184.00	6.09	42.0
Andasol$^{(1)}$	197.9	100.0	400.0	350.00	9.98	39.9
Solúcar PS10$^{(2)}$	204.2	11.00	55.0	24.20	5.02	25.1
Gemasolar$^{(2)}$	205	19.90	195.0	110.00	6.44	63.1

Table 3. *Predicted or actual electricity production by solar photovoltaic farms and thermal solar farms in Spain, versus their electrical capacity and the land area occupied. See table 1 for explanation.*

farms – whether roof-mounted or ground-mounted – satisfy the rough relationship

$$\text{load factor} \simeq \frac{\text{insolation}}{1000\,\text{W/m}^2} \tag{3.1}$$

to within 33%. It is instructive to inspect some of the farms that deviate from this rough relationship. The farm in South Burlington, Vermont (above and to the left in figure 9) has a load factor almost 33% greater than the rough trend; and that farm is composed of two-axis sun-tracking systems. The farm in Rothenbach, Florida (below and to the right in figure 9) has a load factor roughly 40% below the trend; and it is composed of fixed panels that never accurately face the sun, since they are fixed flat on the ground. Sun-tracking panels tend to have higher load factors, and fixed panels and roof-mounted systems tend to have lower load factors. In figure 10 we can observe that the USA farms show a slight anti-correlation between the two performance metrics we have dicussed so far: the solar farms with higher power per unit area (many of which are roof-mounted or have fixed orientation) tend to have lower load factors; and those with the highest load factors – almost all one-axis or two-axis solar trackers – have smaller power per unit area.

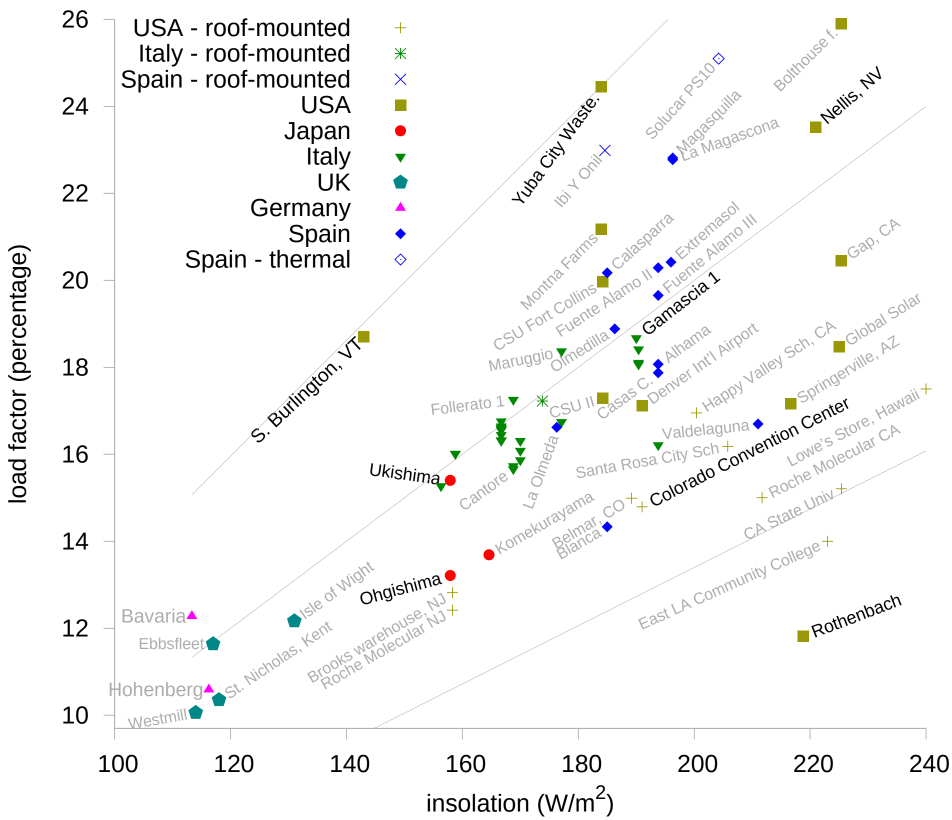

Figure 9. Solar farms' load factors versus their insolation. (See tables 1 and 2 for data.) The grey lines show, as guides to the eye, the relationships (load factor)/(insolation/(1000 W/m^2)) = {1.33, 1.0, 0.67}.

4. The potential role for solar power: what some people say

Britain is one of the least sunny countries, but could solar power nevertheless make a big contribution in places like Britain? According to 'The Eco Experts'†,

> "The UK could meet all of its power needs by devoting just 1% of its land area to solar panels."

The following facts and assumptions underpinned the above statement:

> "In 2009 the UK consumed 352 TWh of electricity. Under optimal conditions (south facing, no shade) a 4-kW solar panel system can produce 3434 kWh per year and takes up 25.7 m^2 of space. This means the UK would need 102 000 000 of these installations to meet all power needs. These would take up 2635 km^2.
>
> "Not really that much space when you think about it. In fact, the numbers above assume the use of relatively small scale home installations.

† http://www.theecoexperts.co.uk/Solar-Panel-Infographic

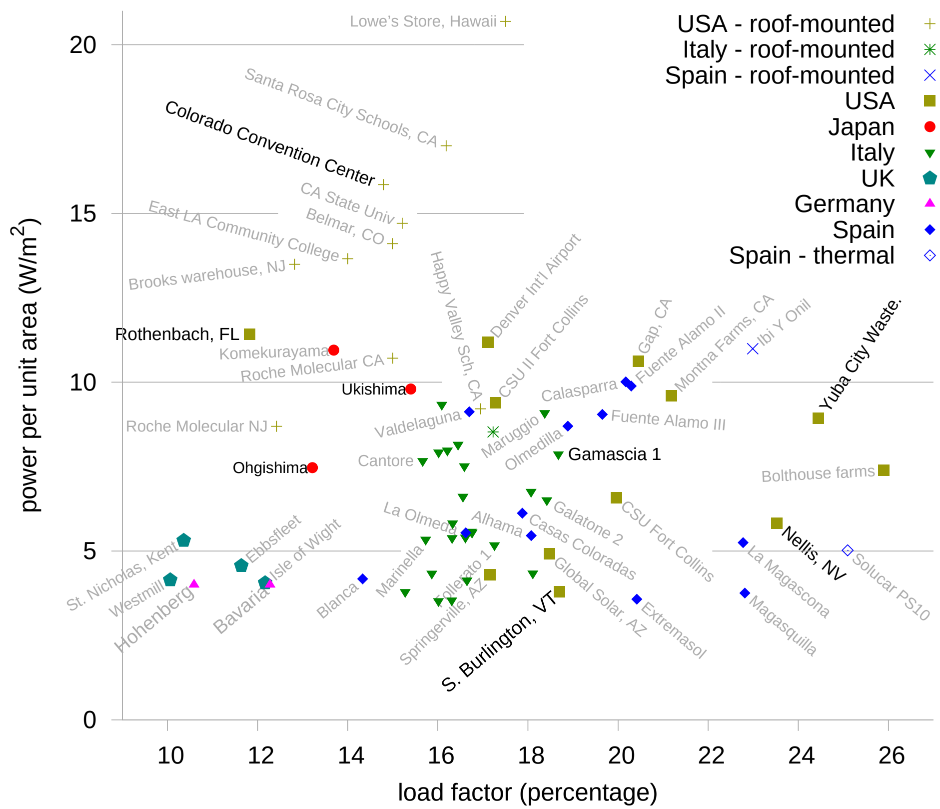

Figure 10. Solar farms' average power per unit land-area versus their load factor (ie, the ratio of their average electrical output to their capacity). Three of the Spanish thermal solar electric power stations have load factors greater than 27% and therefore fall off this chart to the right. (See tables 1 and 2 for data.)

> If larger commercial systems were used, the required space would be further reduced."

I do not dispute The Eco Experts' arithmetic, but I would make the following observations. First, the power consumption quantified here is electricity consumption alone, not including Britain's other forms of energy consumption in transport, heating, and industry. Second, 3434 kWh per year divided by 25.7 m^2 is 15 W/m^2, which is a credible power per unit area for a roof-mounted installation; but, as we saw in the previous section, larger commercial systems today have a significantly *smaller* power per unit land area; on the basis of the UK examples in figure 8, the land area required would be not 1% but 3% of the UK. Third, even if we managed to raise the yield per unit land area to 15 W/m^2, I wonder whether everyone would agree with the value judgement that 1% of the UK's land area is "not really that much space" – for comparison, the land area occupied by all buildings is about 1.2% of the UK, and roads occupy about 1.5%.

Fourth (and to be fair, The Eco Experts acknowledge this point in the small print on their webpage), solar panels only produce power during the day time. And they produce far less in the winter than in the summer. So the UK could only get most of its electricity from from solar panels if it had electricity stores able to serve both night-time demand and much of winter demand. Moreover, if the round-trip efficiency of storage were 75%, then to make up for the 25% loss, the number of solar panels would have to be increased by 33%.

The tables below quantify roughly how much electrical energy one would have to store to make it through a typical night, one winter night, five dull winter days, and an entire winter. To answer the last of these questions I assumed that the output of the panels each day of each month was proportional to the insolation in London shown in figure 1b, that the average output of the panels, year-round, was 40 GW, that perfectly efficient storage was available, and that the electrical demand was 40 GW all the time. The cumulative excess from the panels between March 31st and September 30th, and the cumulative deficit from September 30th to March 31st, are both equal to 2356 hours $\times$ 40 GW (roughly 100 days of average demand). The first table below visualizes the size of energy storage required in terms of the number of kilograms of batteries that would be required per person (if batteries were the chosen storage technology), assuming 60 million people and that the energy density of the batteries is 100 Wh per kg. (This figure lies between lead-acid batteries and lithium-ion batteries, which have energy densities of about 30 Wh per kg and 160 Wh per kg respectively.)

Period	duration (hours)	power (GW)	energy (GWh)	batteries (kg/person)
one typical night	12	35	420	70
one winter night	16	50	800	133
five dull winter days	120	50	6000	1000
summer/winter balancing	2400	40	96 000	16 000

The second table visualizes the storage required in terms of pumped storage, using the “Dinorwig” (10 GWh) as a national unit of energy storage. (Dinorwig is a large pumped storage facility in Wales.) The table gives the lake area required in square kilometres, and in square metres per person, assuming that pumped storage facilities have an areal energy density of 8.2 kWh/m^2 (8.2 GWh/km^2).

Period	energy (GWh)	area (km^2/UK)	area (m^2/person)	number of Dinorwigs
one typical night	420	51	0.85	42
one winter night	800	98	1.63	80
five dull winter days	6000	732	12.2	600
summer/winter balancing	96 000	12 000	195	9600

Note that, under these assumptions, summer/winter balancing would require lakes for pumped storage having a total area that is 5% of the area of the UK! Even the storage for just a single night would require 42 Dinorwigs; the total of the UK’s four pumped storage facilities today is about three Dinorwigs (28 GWh). MacKay

[MacKay, 2008, Chapter 26] identifies 15 candidate locations for further pumped storage in the UK (in Scotland and Wales) and speculates that ten locations in Scotland might be able to store 400 GWh between them.

Batteries and pumped storage are not the only storage solutions. The Danish trick for coping with the intermittency of renewables is to use neighbouring countries as virtual storage, exporting and importing electricity to and from Norway, for example. There are limits to this Norwegian service, however. Norway's total electrical capacity is about 27.5 GW, and their average electrical demand is 12.2 GW, so, unless Norway feels moved to increase its capacity, the maximum it could export to hungry neighbours such as Denmark, Germany, and the UK is roughly 15 GW.

There are thus evident practical challenges involved in delivering the vision (mooted in the first paragraph of section 4) of all UK *electricity* coming from solar, let alone the notion (mooted at the beginning of this paper) that much of *total energy demand* could easily be served by solar power.

5. The potential role for solar power – an optimistic realist's view

By the metric of average power per unit area, solar power is one of the most promising renewables. An individual photovoltaic panel, even in the UK, delivers about 20 W/m^2; a solar photovoltaic park delivers about 5 W/m^2 in duller locations like the UK and up to 10 W/m^2 in sunnier locations; and concentrating solar power in deserts may deliver about 20 W/m^2.

When we take into account the variation in time of solar output, what contribution could solar power credibly make in the UK and in other countries?

To answer this question we need to make judgements about the costs of solar power systems, of energy storage systems, and of transmission systems, and these costs are all uncertain and are expected to change with time. One thing we can say with confidence, however, since the average intensity of sunshine in London is less than half the intensity in Los Angeles (figure 1a), is this: if solar power's costs do continue to fall so that it reaches "grid parity" in Los Angeles, its costs will need to fall by roughly another factor of two to reach grid parity in England (assuming "grid" has roughly the same cost in both locations), and the area of panels required there to deliver a given average output would be doubled.

Obviously solar power will be economic first in locations with more sunshine, and in locations where electricity demand is well-correlated with sunshine, for example places with large air-conditioning demand. (Thanks to climate change and lifestyle change, air-conditioning demand in the UK, currently tiny, may increase in the coming decades.)

Even in a cloudy northerly country like the UK, solar can play a significant role. Solar thermal power, which delivers hot water, has a power per unit area of about 50 W/m^2 in the UK, so a 3-m^2 solar thermal panel can deliver half of the hot-water demand of an average European household [MacKay, 2008, figure 6.3]. In off-grid applications, solar photovoltaics with batteries for electricity storage are already economic in the UK. And once solar power's costs have fallen sufficiently, photovoltaics could supply in the region of 2% of average electricity in a country like the UK without technical difficulty. (This would involve roughly 133 W of peak capacity per person, delivering on average 14 W, which is 2% of an average

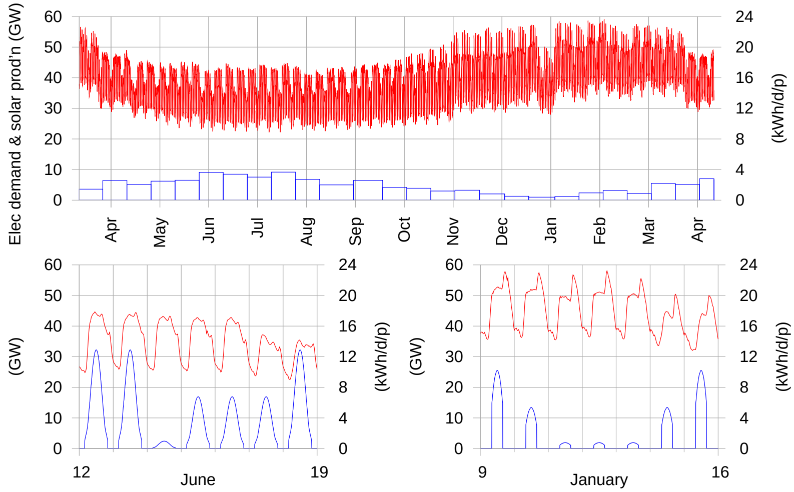

Figure 11. Electricity demand in the UK and modelled solar production, assuming 40 GW of solar capacity. In all three panels the upper red curves show Great Britain's electricity demand, half-hourly, in 2006. The blue data in the upper panel are a scaled-up rendering of the electricity production of a roof-mounted south-facing 4.3-kW 25-m^2 array in Cambridgeshire in 2006. Its average output, year-round, was 12 kWh per day (0.5 kW). The data have been scaled up to represent, approximately, the output of 40 GW of solar capacity in the UK. The average output, year round, is 4.6 GW. The area of panels would be about 3.8 m^2 per person, assuming a population of roughly 60 million. (For comparison, the land area occupied by buildings is 48 m^2 per person.) In the lower two panels, the blue curves show, for a summer week and a winter week, the computed output of a national fleet of 40 GW of solar panels, assuming those panels are unshaded and are pitched in equal quantities in each of the following ten orientations: south-facing roofs with pitch of (1) 0°, (2) 30°, (3) 45°, (4) 52°, and (5) 60°; (6) south-facing wall; and roofs with a pitch of 45° facing (7) southeast, (8) southwest, (9) east, and (10) west. On each day, the theoretical clear-sky output of the panels is scaled by a factor of either 1, 0.547, or 0.1, to illustrate sunny, partially sunny, and overcast days. Note that on a sunny weekend in summer, the instantaneous output near midday comes close to matching the total electricity demand. Thus if solar PV is to contribute on average more than 11% of GB electricity demand without generation being frequently constrained off, significant developments will be required in demand-side response, large scale storage, and interconnection.

per-capita electricity consumption of 680 W; for comparison, Germany already has about 300 W of solar peak capacity per person, and in 2011 solar power delivered on average 25 W per person, which is roughly 3% of average German per-capita electricity consumption; on a sunny holiday in May 2012, the peak output from solar power at midday was about 40% of German electricity demand†).

For solar photovoltaics to supply 6% or more of today's *average* electricity demand in the UK would involve some technical challenges. The UK's National Grid (personal communication) have advised me that if 22 GW of solar capacity (370 W of capacity per person) were attached to today's grid, then the system would, at

† `http://www.pv-magazine.com/news/details/beitrag/germany--record-40-percent-solar-weekend_100006953/#axzz2JGVmUlkA`

some times on some sunny summer days, be unacceptably challenging to control and unacceptably lacking in robustness to a sudden fall in demand: the control of the grid's frequency relies on having sufficient inertial generators on the system; in their advice to me, National Grid reckoned that 40% of demand at any time should be served by inertial generators, and they assumed that solar and wind generators would contribute no inertia. This constraint could in due course be relaxed if additional inertial services could be supplied (for example by wind generators that incorporate energy stores and can therefore synthesize inertial properties) or if control-commands could when necessary be issued to solar generators to instruct them to reduce their output. (Future generation codes in the UK will require solar generators to have the capability to respond to such signals.)

Let's assume that these technical constraints can be solved. What if solar photovoltaics supplied 11% or more of today's *average* electricity demand in the UK? Figure 11 shows the time-variation of the output of a simply-modelled fleet of 40 GW of solar panels in the UK (670 W of capacity per person), whose average output (4.4 GW, if we assume a load factor of 0.11) would equal 11% of current electricity demand. The total output is occasionally close to the total electricity demand; at these levels of solar capacity, peaks of solar output would certainly cause electricity supply to be shed, unless our electricity system is enhanced by the addition of (a) large pieces of flexible demand; (b) large interconnectors to other countries willing to buy excess electricity; or (c) large-scale energy storage.

We now explore some of these three options, starting with storage.

(*a*) *Balancing large solar generation with electricity storage*

The highest ambition for domestic solar photovoltaics would be for them to be able to emulate baseload generation, with the help of electricity storage – probably the most costly of the three options just listed. Figure 12 displays the cost of emulating baseload with an electricity store, as a function of the photovoltaic cost and the storage cost, assuming a sunny location with a load factor of 20%. To illustrate the methodology underlying this figure, consider a solar-panel cost of \$1000 per kilowatt of capacity, *including all peripherals except storage*, and consider a storage cost of \$125 per kWh. (This is much cheaper than the cheapest of today's rechargeable batteries, and comparable to the cost of pumped storage.) Under these assumptions, panels with an average output of 1 kW would cost \$5000; we assume that 60% of the delivered electricity goes via a store with a round-trip efficiency of 75%, so the panels for a system with 1 kW output, post-store, cost \$6000. The additional cost of storage able to keep delivering 1 kW for 14 hours of darkness (the duration of night in winter at the latitude of Los Angeles – 34°) would be \$1750 (which, added to the panels' cost of \$6000, gives the \$7750 shown in figure 12a). The cost of storage able to keep delivering 1 kW for 5 dull days would be \$15 000 (which gives a total cost of \$21 000 as shown in figure 12b). Assuming a working life of 20 years, electricity from the system just described would cost 12¢ per kWh; for comparison, the consumer wholesale price of electricity in the UK is about 5.5 p per kWh (8.6¢) in 2012. I emphasize that I am not asserting that the costs just mentioned (solar-panel cost of \$1000 per kilowatt of solar capacity and \$125 per kWh of storage) are correct; the reader can use figures 12a and b to read out the

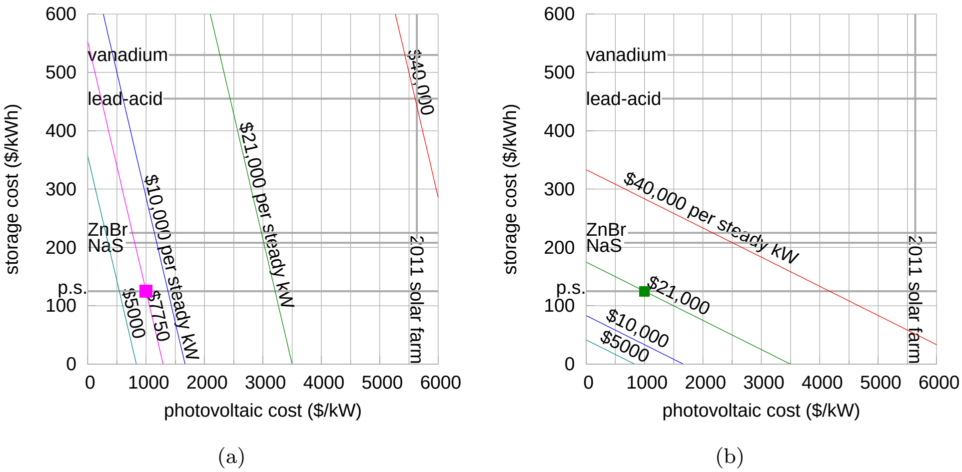

Figure 12. Contour plot of the total cost of a photovoltaic system, in a sunny location, capable of giving a steady 1-kW output with (a) 14 hours of storage (as might be appropriate in a location such as Los Angeles); (b) 120 hours of storage (as might be appropriate in cloudier locations), as a function of the cost of the panels and the cost of storage. Assumptions: load factor, 20%; efficiency of electrical storage, 75%; fraction of final electricity that comes through the store, 60%. The capital costs per kW are equivalent to the following undiscounted costs per kWh, assuming 20 years' operation: $5000 per kW ↔ 2.9¢ per kWh; $7750 per kW ↔ 4.4¢ per kWh; $10 000 per kW ↔ 5.7¢ per kWh; $21 000 per kW ↔ 12.0¢ per kWh; $40 000 per kW ↔ 22.8¢ per kWh. Costs of battery storage are from Poonpun and Jewell [2008]. Cost of pumped storage (p.s., $125 per kWh) is based on Auer and Keil [2012]. The cost of the Vermont solar farm (section 3), built in 2011, was $5630 per kW of capacity ($12 million for 2130 kW), without electricity storage. Note that the total cost of this solar farm is more than three times the cost of its photovoltaic modules (roughly $1750 per kW).

cost per kW of output for any cost assumptions, and I only mentioned these costs to aid and illustrate the explanation of the figure.

We can conclude that, for photovoltaics to deliver cost-competitive baseload electricity in a sometimes-cloudy location, we need two cost breakthroughs: not only does solar need to have a ballpark cost of one dollar per watt *including peripheral plant*, but also the cost of storage needs to fall to a ballpark cost of $125 per kWh or below. The former breakthrough may be happening this decade, but the storage-cost breakthrough is not yet here, and pumped storage is unlikely to be deployable at the required scale. If 120 hours (5 dull days) of storage were provided for a solar farm by dedicated pumped storage, the lake area required in a mountainous location would be about the same as the area of the solar panels in the farm. (Dinorwig, a 9-GWh pumped storage facility using a pair of lakes with a vertical separation of 500 m and a combined area of about 1.1 km^2, stores 8.2 kWh per square metre of lake area [MacKay, 2008, p 190–193]; at a ratio of 120 kWh per average kW of solar, that implies a pumped storage area of 15 m^2 per kW of solar output.) Two electricity storage technologies that may have the potential to match or beat the cost of pumped storage, and that would have much smaller land requirements, are compressed-air energy storage [Succar and Williams, 2008] and reversible thermal storage using high-efficiency heat pumps [Howes, 2012, Ruer et al., 2010, White et al., 2012, White, 2011].

(*b*) *Balancing large quantities of solar power with storable products*

Stepping back from this highest ambition, an alternative way of handling solar intermittency would be for solar to play a role in flexible production of storable energy-intensive products that are required in appropriately large quantities. (The economics will be most favourable if storage is relatively cheap, if the capital cost of the production machinery is relatively cheap, and ramping production up and down with the sunshine is technically possible.) For six storable substances (ice, ammonia, hot water, aluminium, hydrogen, and gasoline), figure 13 shows on the horizontal axis rough estimates of the energy intensity of production in kWh of electricity per kg, and on the vertical axis a guess of the demand that exists or could exist for each substance, in kg per year per person. The contours show how much electrical power, in watts per person, would be consumed by producing each substance at the given rate.

Ice. The best large-scale commercial ice production has an energy intensity of 270 kJ per kg (for water-cooled ice-makers) or 330 kJ per kg (for air-cooled ice-makers). Figure 13 shows the mid-point, 300 kJ/kg (0.083 kWh/kg). (Thermodynamics would allow lower energy intensities – the latent heat of fusion of ice is 333 kJ/kg, and the heat removal to cool water from 20 °C to 0 is 80 kJ/kg, so the energy intensity of a freezer with a coefficient of performance of, say, 4 would be about 104 kJ/kg; the thermodynamic limit when the external temperature is 35 °C is a coefficient of performance greater than 7 [MacKay, 2008, p 300].) Ice production in the USA amounts to about 188 kg per year per person [Madison Gas and Electric, 2012]. As figure 13 shows, ice production at these levels consumes 1.8 W per person.

Ammonia. World ammonia production is 131 million metric tons per year (about 22 kg per person per year), mainly used for making fertilizers. Ammonia is produced from hydrogen and nitrogen by the Haber–Bosch process. To show ammonia in figure 13, I assumed that the hydrogen could be produced by electrolysis with the energy intensities discussed in the hydrogen paragraph below. Ammonia production at these levels could consume roughly 20 W per person of electricity. In principle, ammonia could also be used as a fuel for transport, in which case higher electrical powers could be consumed, equivalent to those for hydrogen below.

Hot water. For a temperature rise of 60 °C, water can store 0.07 kWh of heat per kg; if the heat is delivered by a heat pump with an optimistic coefficient of performance of 4, then the electrical energy intensity of making hot water is 0.017 kWh per kg. If hot water demand is assumed to be about 33 kg per day per person (12 000 kg/year/person), the average electricity demand it could consume is in the range 25–100 W per person. In principle, sufficiently large volumes of hot water could store energy for space heating; a space heating demand of 20 kWh per day per person would correspond to a hot water demand of 100 000 kg per year per person. Space heat could also be stored from one month to another in hot rocks. Inter-seasonal storage of heat derived from solar thermal collectors has been demonstrated in a large insulated pond by Max Fordham architects at a retrofitted English office building, Beaufort Court; and in an underground store associated with

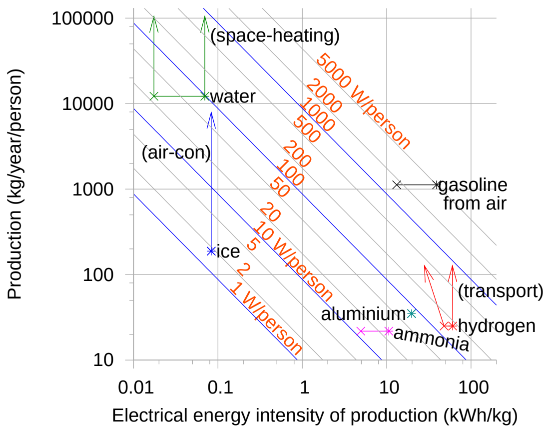

Figure 13. Contour plot of potential average consumption of electrical power as a function of production and energy-intensity of storable materials. The points show these two properties for six materials: ice, ammonia, aluminium, hot water, hydrogen, and gasoline from thin air. Where there are two points, the right-hand coordinate indicates proven achievable energy intensity of production, and the left-hand coordinate shows the conceivable energy intensity with efficiency improvements. For ice, ammonia, aluminium, hot water, and hydrogen, the production shown is today's production; the arrows indicate levels to which production could rise if stored ice were used as a carrier of cold for air-conditioning, if stored water were used as a carrier of heat for space heating, and if hydrogen took a significant role in transport. For gasoline production from air, the "production" shown is today's per-capita consumption of transport fuels in the UK.

50 homes at Drake Landing in Canada. This underground store uses a cylindrical piece of ground of depth 37 m and diameter 35 m to store roughly 1 GWh of heat. British company ICAX builds underground thermal stores that are used in winter to supply heat to ground-source heat pumps for space heating.

Aluminium. The UK's aluminium consumption is estimated to be about 35 kg per year per person [Allwood and Cullen, 2011]. Roughly half of the energy cost of aluminium production goes into electrolysis, and it is the electrical intensity of electrolysis that I have shown in figure 13: 71 MJ per kg (20 kWh/kg). Aluminium electrolysis at a rate of 35 kg per year per person would consume about 80 W per person.

Hydrogen. Today's production of hydrogen is about 50 million tonnes per year, which, if we deem most of it to be shared between 2 billion people in the developed world, is a per-capita production of 25 kg/year. The IEA anticipate that hydrogen production for energy applications could rise to 12.5 EJ per year by 2050 – about 127 kg per year per person. The intensity of commercial electrolysis today ranges from 48 to 60.5 kWh per kg of hydrogen; in the future, new production technologies are expected to become commercial with intensities in the range 28–60 kWh per kg [International Energy Agency, 2007]. Figure 13 shows four points for hydrogen, two for the current range of intensities and today's production, and two arrow-tips for the future range of intensities and projected production. The maximum projected electricity consumption for hydrogen production is roughly 500 W per person.

Gasoline from air. Direct synthesis of hydrocarbons with air capture of CO_2 could guzzle the highest amounts of electricity, under the following assumptions. The thermodynamic limit for CO_2 capture from thin air is 0.13 kWh per kg of CO_2. The energy cost of making gasoline (or a similar hydrocarbon) from thin air would be dominated by the cost of reversing the reaction

$$1\,\text{kg of gasoline} \longrightarrow 13\,\text{kWh} + 3\,\text{kg CO}_2.$$

At the limit, thermodynamics might permit this reaction to be reversed for a payment of 13 kWh per kg of gasoline, for a total cost (including ideal air-capture) of 13.4 kWh per kg. Realistically, if air-capture and fuel synthesis using electricity have an efficiency of 38% (or better), then the energy intensity might be 35 kWh per kg (or less). For the per-capita production in figure 13, I have taken today's per-capita consumption of liquid fuels in the UK, 1124 kg per year. Of the six storable products, gasoline from thin air could consume the most electricity – in the ballpark of 2000 to 4500 watts per person, if today's consumption of liquid fuels were sustained. Given how difficult it is to electrify some forms of transport (for example, aviation, shipping, and heavy goods vehicles), the creation of transport fuels from excess electricity seems an especially important idea. There is a growing literature on this topic and efficiencies of 38% have been demonstrated in the laboratory. It has been suggested that the simplest and most efficient 'electrofuel' to make would be methanol, that the electricity-to-liquid efficiency of methanol production might be about 46%, and that methane could also be produced with an electricity-to-methane efficiency of 48% [Pearson et al., 2012, Jiang et al., 2010]. Incidentally, if this electricity–to–methane technology were to feed a modern methane–to–electricity plant at another time, then an electricity storage option would be delivered having a round-trip efficiency of 28%. Returning to transport applications, we can visualize powering all today's ships and planes from clean electricity as follows. In the year 2000, shipping consumed 7.32 EJ per year (equivalent to 231 GW), and aviation consumed 8.95 EJ per year (284 GW) [Kahn Ribeiro et al., 2007]. If both these liquid power demands were met from electricity via processes with an efficiency of 38% then the total electrical power required would be 1355 GW (more than half the world's current electricity consumption), which could be delivered, on average, by any of: 1355 standard nuclear power stations; onshore or offshore windfarms occupying an area of about 540 000 km^2 (that's equal to twenty-four New Jerseys, or 1.5 Germanys) – assuming a power per unit area of 2.5 W/m^2; or solar farms in sunny locations occupying an area of 136 000 km^2 (six New Jerseys) – assuming a power per unit area of 10 W/m^2. (One New Jersey is roughly equal to one Wales.) Any of these three ideas sound challenging, but it is possible that society might prefer one of them, or a mixture of them, to another option for decarbonizing aviation and shipping, namely energy crops, which would require about one million km^2 to deliver 7.32 + 8.95 EJ per year – assuming that energy crops can deliver transport fuels with a net production rate of 0.5 W/m^2, when energy inputs and processing losses are taken into account. One million km^2 is 45 New Jerseys.

(*c*) *Transporting solar power from deserts*

Many enthusiasts for solar power (eg, `www.desertec.org`) envision a large energy contribution coming to high-consuming, high-population-density regions in

assumed CSP power per unit area	15 W/m^2	20 W/m^2
area for 44.4 GW (avg) of CSP	2960 km^2	2220 km^2
land for 50 GW (peak) HVDC power lines	1500 km^2	1500 km^2
total area	4460 km^2	3720 km^2
net power per unit area	9.0 W/m^2	10.7 W/m^2

Table 4. *Power per unit area of a very large concentrating solar power station, including its high-voltage transmission lines, delivering 40 GW, allowing for 10% loss in transmission. The area of Greater London is 1580 km^2.*

relatively cloudy locations from concentrating solar power stations in deserts thousands of kilometres away. Storage and transmission of this energy could be handled in various ways. One option is for the concentrating power station to store high-temperature heat from day into night in the form of molten salt, before conversion of the heat to electricity. The land occupied by the molten-salt store is a tiny fraction of the land occupied by the concentrating mirrors of the Andasol power station in Spain. Table 4 shows the land area required if the power station delivers 40 GW of electricity on average through high voltage DC power lines over the distance from the Sahara to Surrey: the power station itself occupies between one and two Greater Londons, and the power lines occupy another Greater London.

An alternative way to transmit power long distances would be to convert the power into chemical form – for example, liquid hydrocarbon – and send the chemicals by ship. Allowing for inefficiency in conversion (as discussed in the previous section), the land area of the solar power station in the desert might need to be roughly doubled, but the long-distance power lines would be eliminated, and the delivered product would be storable and useful for difficult-to-electrify applications such as transport. To visualize the scale of infrastructure required, a power flow of 40 GW can be embodied by *two supertankers per day* full of liquid fuel.

The ideas of storing large quantities of useful energy when nature provides it, and of transmitting useful energy long distances from one country to another, are not new. In the 1890s, ice houses were a common sight, and Norway exported 340 000 tons of ice to England each year.

6. Conclusion

"Can solar deliver?" – without doubt, the answer is yes. I expect solar power initially to make its biggest contributions through solar thermal heat and through low-cost photovoltaics deployed in locations where there is a well-matched air-conditioning demand. The economics will always favour locations with high insolation. Concentrating solar power in deserts has enormous technical potential for delivery of industrial heat and electricity, and I find it hard to imagine the world achieving the climate-change action aspired to by recent UNFCCC negotiations without significant deployment of solar power in sunny locations. But we must have no delusions about the area required for large-scale solar power; about the challenge of transmitting energy over large distances; about the additional costs of handling intermittency; and about the need for breakthroughs not only in the whole-system costs of photovoltaics but also in the cost of systems for storing energy.

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Appendix A. Solar farm data

The data in tables 1–3, figures 8–10 and figures 14 were sourced as follows.

Production data for the Japanese farms at Ukishima and Ogishima are actual data from their first year of operation (sources: `www.tepco.co.jp/en/news/topics/images/120810a.pdf`, `www.tepco.co.jp/en/news/topics/images/121219a.pdf`). Data for Komekurayama are estimates (source: `www.tepco.co.jp/en/challenge/energy/megasolar/`).

Data for most of the farms in USA and Spain, and half the farms in Italy are estimates drawn from Fotowatio Renewable Ventures 2010 Summary of Activities `www.qualitasequity.com/en/memoria_frv_ing.pdf`, with checks, corrections, and actual production data from
`www.exenewable.com/projectProfile.asp?id=20819`,
`www.frv.com/portfolio-en/the-usa/belmar-complex-175-mwp`,
`www.frv.com/portfolio-en/the-usa/california-state-university-fresno-117-mwp`,
`www.denver.org/denver-meetings-conventions/green-meetings/colorado-convention-center`,
`www.frv.com/portfolio-en/the-usa/csu-fort-collins-fase-i-eeuu`,
`www.news.colostate.edu/Release/4991`,
`www.campusgreenbuilder.org/userfiles/file/ELAC%20-%20CES_Final.pdf`,
`www.frv.com/portfolio-en/the-usa/gap-inc-106-mwp`,
`commercial.sunpowermonitor.com`,
`www.frcc.com/Planning/Shared%20Documents/FRCC%20Presentations%20and%20Utility%2010-Year%20Site%20Plans/2011/2011_TYSP_FPL.pdf`,
`www.appeal-democrat.com/articles/yuba-120134-city-blood.html`,
`opud.net/opud-blog/solar-project`,
`www.invitalia.it/site/eng/home/media-center/news/articolo5178.html`,
`www.sunnyportal.com/` (which has actual production data for Gamascia 1),
`www.torresolenergy.com/EPORTAL_DOCS/GENERAL/SENERV2/DOC-cw4cb709fe34477/GEMASOLARPLANT.pdf`,
sources cited in MacKay [2008], and area measurements using Google maps.

Data from one solar farm in the FRV annual report (Stornara farm, located in Ginosa, Puglia, Italy) was excluded on the grounds that the load factor implied by the predicted production (12 941 MWh/year from a capacity of 5.92 MW) was grossly at variance with the load factors of all similar nearby farms built by the same company, and no alternative source for production data could be found.

Data for the other farms in Italy are estimates from `pensatopartners.files.wordpress.com/2012/04/20120406-eng-pp-company-presentation.pdf`.

Data for Springerville Generating Station Solar System are actual data from `www.tep.com/tracker/systems/springerville/`.

Data for UK are from `www.vogtsolar.co.uk` and and `westmillsolar.coop`.

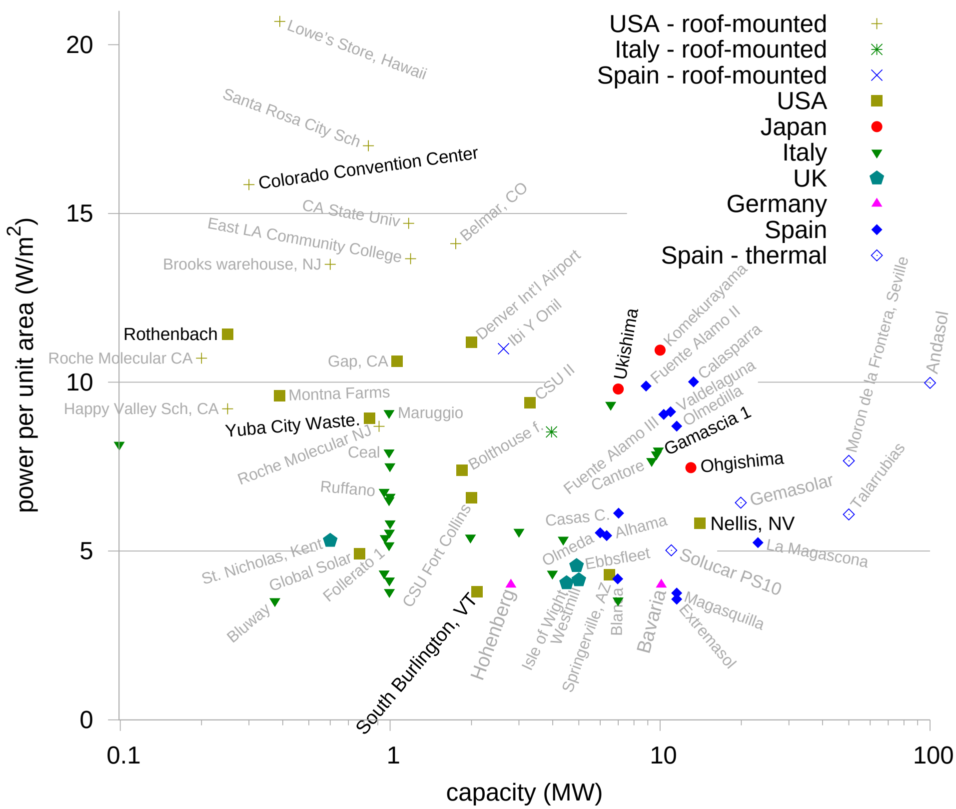

Figure 14. Solar farms' average power per unit land-area versus their capacity. (See tables 1–3 for data.)

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