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

David J. C. MacKay
Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK

Taking the UK 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 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, then we obtain the average primary energy consumption per unit area, which for the UK 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 the 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, Germany, and Vermont, USA, 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-consumption 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, then we need new methods for energy storage; very-large-scale solar either would 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.

1. Introduction

The enormous technical potential of solar power is often pointed out. Eicke Weber, the Director of the Fraunhofer Institute for Solar Energy Systems in Freiburg, Germany, 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’ (National Geographic; http://ngm.nationalgeographic.com/print/2009/09/solar/johnson-text). 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, UK, is less than half the intensity in Los Angeles, CA (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 in summer (figure 2). Moreover, in the UK, daily electricity demand has its maximum not at noon but at 18.00. 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 100-fold greater than countries to the left, and countries at the top consume roughly 100 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 USA, Sudan, Brazil, Portugal, China, India, Bangladesh, the UK and the Republic of 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 UK, Germany and Japan. Figure 5 gives a longer view of this trend over the last few centuries.

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
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’s 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/) (Online version in colour.)

Arabia and Norway (towards the top left of Figure 3), Mexico (in the middle), Guatemala and Haiti (towards the bottom right) all consume about 0.1 W m\(^{-2}\). While 0.1 W m\(^{-2}\) is the world’s average power consumption per unit area, 78 per cent of the world’s population live in countries that have a power consumption per unit area greater than 0.1 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 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 the Scottish highlands has a raw power per unit area of roughly 0.24 W m\(^{-2}\); energy crops in Europe deliver about 0.5 W m\(^{-2}\); onshore and offshore wind farms in England and Wales deliver roughly 2.5 W m\(^{-2}\); wind farms on Scottish hilltops deliver roughly 3.5 W m\(^{-2}\) [3]; as we will see in the following section, solar photovoltaic farms in northern Europe deliver 4–5 W m\(^{-2}\) and, even
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. (Online version in colour.)

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\(^{-2}\) [4, p. 184]. Figure 6 shows some of these renewable power densities by 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 per cent. The same goes for concentrating solar power stations: the Solúcar PS10 solar tower has a mirror-to-land-area ratio of 14 per cent. In principle, some of these renewable power densities might be increased by technological progress—for example, Dabiri [5] 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 [5] 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-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
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 km² (e.g. 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. Seventy-eight per cent 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.) (Online version in colour.)

(originally described by Loyd [6]) seems a promising way to deliver such improvements at low cost. Similarly, I acknowledge that 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 cannot perform beyond the Shockley–Queisser limit [7]; 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 [8], 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 in Wales, for example, processes 220 000 barrels of crude oil per day (16 GW) and has an area of 4 km²—a rough power per unit area of 4000 W m$^{-2}$. The Longannet power station in Scotland (2.4 GW capacity) occupies 1.6 km², 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 of 740 W m$^{-2}$. Nuclear power facilities have a similar power per unit area to coal [3]. 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 and 1300 km² (a route length of about 13 000 km, multiplied by a ‘width of land occupied’ of between 18 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 $(42 \text{ GW})/(57 \text{ km}^2 + 230 \leftrightarrow 1300 \text{ km}^2) = 146 \leftrightarrow 31 \text{ W m}^{-2}$. 
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 USA, Sudan, Brazil, Portugal, China, India, Bangladesh, the UK and the Republic of Korea. Seventy-eight per cent of the world’s population live in countries that have a power consumption per unit area greater than 0.1 W m\(^{-2}\). (Online version in colour.)

Figure 5. Power consumption per person versus population density, from 1600 or 1800 to 2005. OECD, Organization for Economic Cooperation and Development. Sources: references [1,2]. (Online version in colour.)
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, the Republic of 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. [9] and Jochem [10] for discussion of the research and development challenges of delivering a 66% reduction in per capita energy consumption in a European country); lifestyle 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 per cent decarbonization. The Carbon Plan sketches a corridor of pathways in which: per capita demand in the UK falls by between 31 and 54 per cent; nuclear power generation capacity increases from today’s 10 GW to between 16 and 75 GW; renewable electricity-generation capacity increases from today’s 10 GW to between 22 and 106 GW; carbon capture and storage electrical capacity increases to between 2 and 40 GW; and bioenergy use increases from today’s 73 TWh yr$^{-1}$ to between 180 and 470 TWh yr$^{-1}$ (21–54 GW).

3. The power per unit area of solar farms

AllEarth Renewables (www.allearthrenewables.com), a company based in Vermont, USA, provides detailed production data for its photovoltaic installations. The largest solar farm in
Vermont, site 316, has 382 Sun-tracking modules, with a combined peak capacity of 2.1 MW. The farm’s land area is 0.1 km². 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 per cent is presumably the product of a solar module efficiency of about 19 per cent (including DC-to-AC conversion losses) and a filling factor (functional panel area to land area ratio) of about 14 per cent. 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, Germany, occupies about 30.6 ha 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 [11]; the 2.8 MW Hohenberg/Marktleugast farm, also in Germany, 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 [12]. 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 re-optimized 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, 20 and 15 W m⁻², respectively, if we assume a module efficiency of 20 per cent and a filling factor of 80 per cent.

Figures 8–10 and tables 1 and 2 contain data from the above-mentioned 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 dataset should be treated with caution, because 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 area versus the local insolation (i.e. average incident solar flux per unit of horizontal land area). Figure 8 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 per cent and 86 per cent greater, the power per unit area of every ground-based solar farm is between 3.5 and 10 W m⁻². Fourth,
Figure 8. Solar farms' average power per unit land area versus the local insolation (i.e. 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 have 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: $1 \text{ W} = 8.766 \text{ kWh per year}$.) (Online version in colour.)

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

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 per cent are common, and almost all the farms—whether roof-mounted or ground-mounted—satisfy the rough relationship

$$\text{load factor} \simeq \frac{\text{insolation}}{1000 \text{ W m}^{-2}}$$

(3.1)

to within 33 per cent. It is instructive to inspect some of the farms that deviate from this rough relationship. The farm in South Burlington, VT (above and to the left in figure 9), has a load factor almost 33 per cent greater than the rough trend; and that farm is composed of two-axis Sun-tracking systems. The farm in Rothenbach, FL (below and to the right in figure 9), has a load factor roughly 40 per cent below the trend; and it is composed of fixed panels that never accurately face the Sun, because 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.
Table 1. Predicted or actual electricity production by solar photovoltaic farms in various countries versus their electrical capacity and the land area occupied. ‘Insolation’ is the average power per unit of horizontal area in the vicinity of the farm, from www.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 are labelled by an asterisk denote actual production; otherwise, the production stated is a published estimate. These data are shown graphically in figures 8–10, and the figure in appendix A.

<table>
<thead>
<tr>
<th>Name</th>
<th>Insolation (W m(^{-2}))</th>
<th>Capacity (MW)</th>
<th>Area (ha)</th>
<th>Production (GWh yr(^{-1}))</th>
<th>Power per Area (W m(^{-2}))</th>
<th>Load Factor (%)</th>
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<td>Bavaria solarpark(^b)</td>
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\(^a\) Denotes fixed structure (not Sun-tracking).
\(^b\) Denotes a single-axis solar-tracking system.
\(^c\) Denotes a two-axis solar tracker.
\(^d\) Denotes roof-mounted installations.
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.

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<td>6.56</td>
<td>11.30</td>
<td>9.25</td>
<td>9.34</td>
<td>16.1</td>
</tr>
<tr>
<td>Anagni FRb</td>
<td>170</td>
<td>6.98</td>
<td>32.1</td>
<td>9.98</td>
<td>3.54</td>
<td>16.3</td>
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<tr>
<td>Bluway</td>
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<td>0.37</td>
<td>1.70</td>
<td>0.53</td>
<td>3.52</td>
<td>16.0</td>
</tr>
<tr>
<td>Cantore</td>
<td>163.8</td>
<td>9.31</td>
<td>19.00</td>
<td>12.78</td>
<td>7.67</td>
<td>15.7</td>
</tr>
<tr>
<td>Capri</td>
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<td>3.00</td>
<td>9.00</td>
<td>4.40</td>
<td>5.58</td>
<td>16.7</td>
</tr>
<tr>
<td>Cassino</td>
<td>170</td>
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<td>14.60</td>
<td>5.55</td>
<td>4.34</td>
<td>15.9</td>
</tr>
<tr>
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<td>2.00</td>
<td>1.39</td>
<td>7.93</td>
<td>16.0</td>
</tr>
<tr>
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<td>0.20</td>
<td>0.14</td>
<td>8.16</td>
<td>16.4</td>
</tr>
<tr>
<td>Fiumicino</td>
<td>193.8</td>
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<td>20.00</td>
<td>14.00</td>
<td>7.99</td>
<td>16.2</td>
</tr>
<tr>
<td>Follerato</td>
<td>163.8</td>
<td>0.99</td>
<td>3.30</td>
<td>1.50</td>
<td>5.18</td>
<td>17.3</td>
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<tr>
<td>Galatone</td>
<td>190.4</td>
<td>0.95</td>
<td>3.96</td>
<td>1.51</td>
<td>4.34</td>
<td>18.1</td>
</tr>
<tr>
<td>Galatone</td>
<td>190.4</td>
<td>0.99</td>
<td>2.80</td>
<td>1.60</td>
<td>6.51</td>
<td>18.4</td>
</tr>
<tr>
<td>Gamascia</td>
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<td>9.69</td>
<td>23.00</td>
<td><strong>15.86</strong></td>
<td>7.87</td>
<td>18.7</td>
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<tr>
<td>Maruggio</td>
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<td>2.00</td>
<td>1.59</td>
<td>9.10</td>
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</tr>
<tr>
<td>Ruffano</td>
<td>190.4</td>
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<td>2.54</td>
<td>1.50</td>
<td>6.76</td>
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<tr>
<td>Geosis</td>
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<td>1.45</td>
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<td>Marinella</td>
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<td>5.34</td>
<td>15.7</td>
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<tr>
<td>Minervino</td>
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<td>8.53</td>
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<tr>
<td>Posta Piana</td>
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<td>2.80</td>
<td>1.43</td>
<td>5.83</td>
<td>16.3</td>
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<tr>
<td>Posta Conca</td>
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<td>1.00</td>
<td>2.50</td>
<td>1.45</td>
<td>6.62</td>
<td>16.6</td>
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<td>6.10</td>
<td>2.89</td>
<td>5.40</td>
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<tr>
<td>Servigliano</td>
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<td>0.99</td>
<td>4.00</td>
<td>1.33</td>
<td>3.79</td>
<td>15.3</td>
</tr>
<tr>
<td>Siponto</td>
<td>166.7</td>
<td>0.96</td>
<td>2.90</td>
<td>1.37</td>
<td>5.39</td>
<td>16.3</td>
</tr>
<tr>
<td>Torremaggiore</td>
<td>166.7</td>
<td>1.00</td>
<td>2.20</td>
<td>1.45</td>
<td>7.52</td>
<td>16.6</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ebbsfleet</td>
<td>117</td>
<td>4.90</td>
<td>12.50</td>
<td>5.00</td>
<td>4.56</td>
<td>11.6</td>
</tr>
<tr>
<td>Isle of Wight</td>
<td>131</td>
<td>4.50</td>
<td>13.50</td>
<td>4.80</td>
<td>4.06</td>
<td>12.2</td>
</tr>
<tr>
<td>Saint Nicholas, Kent</td>
<td>118</td>
<td>0.60</td>
<td>1.17</td>
<td>0.54</td>
<td>5.31</td>
<td>10.4</td>
</tr>
<tr>
<td>Westmill, Watchfield</td>
<td>114</td>
<td>5.00</td>
<td>12.14</td>
<td>4.41</td>
<td>4.14</td>
<td>10.1</td>
</tr>
</tbody>
</table>

See table 1 for explanation.

Factors. In Figure 10, we can observe that the USA farms show a slight anti-correlation between the two performance metrics we have discussed 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.
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 such as Britain? According to ‘The Eco Experts’ (http://www.theecoexperts.co.uk/Solar-Panel-Infographic):

The UK could meet all of its power needs by devoting just 1 per cent 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 m² of space. This means the UK would need 102 000 000 of these installations to meet all power needs. These would take up 2635 km².

Not really that much space when you think about it. In fact, the numbers above assume the use of relatively small-scale home installations. If larger commercial systems were used, the required space would be further reduced.
Figure 9. Solar farms’ load factors versus their insolation. (See tables 1–3 for data.) The grey lines show, as guides to the eye, the relationships \( \frac{\text{load factor}}{\text{insolation} (1000 \text{ W m}^{-2})} = \{1.33, 1.0, 0.67\} \). (Online version in colour.)

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 per cent but 3 per cent 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 per cent 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 per cent of the UK, and roads occupy about 1.5 per cent.

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 daytime. And they produce far less in the winter than in the summer. So the UK could only get most of its electricity 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 per cent, then to make up for the 25 per cent loss, the number of solar panels would have to be increased by 33 per cent.

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 31st March and 30th September, and the cumulative deficit from 30th September to 31st March, are both equal to 2356 h × 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 kg\(^{-1}\). (This figure lies between lead–acid batteries and lithium-ion batteries, which have energy densities of about 30 and 160 Wh kg\(^{-1}\), respectively.)

<table>
<thead>
<tr>
<th>period</th>
<th>duration (h)</th>
<th>power (GW)</th>
<th>energy (GWh)</th>
<th>batteries (kg per person)</th>
</tr>
</thead>
<tbody>
<tr>
<td>one typical night</td>
<td>12</td>
<td>35</td>
<td>420</td>
<td>70</td>
</tr>
<tr>
<td>one winter night</td>
<td>16</td>
<td>50</td>
<td>800</td>
<td>133</td>
</tr>
<tr>
<td>five dull winter days</td>
<td>120</td>
<td>50</td>
<td>6000</td>
<td>1000</td>
</tr>
<tr>
<td>summer/winter balancing</td>
<td>2400</td>
<td>40</td>
<td>96 000</td>
<td>16 000</td>
</tr>
</tbody>
</table>

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$^{-2}$).

<table>
<thead>
<tr>
<th>period</th>
<th>energy (GWh)</th>
<th>area (km$^2$/UK)</th>
<th>(m$^2$ per person)</th>
<th>number of Dinorwigs</th>
</tr>
</thead>
<tbody>
<tr>
<td>one typical night</td>
<td>420</td>
<td>51</td>
<td>0.85</td>
<td>42</td>
</tr>
<tr>
<td>one winter night</td>
<td>800</td>
<td>98</td>
<td>1.63</td>
<td>80</td>
</tr>
<tr>
<td>five dull winter days</td>
<td>6000</td>
<td>732</td>
<td>12.2</td>
<td>600</td>
</tr>
<tr>
<td>summer/winter balancing</td>
<td>96 000</td>
<td>12 000</td>
<td>195</td>
<td>9600</td>
</tr>
</tbody>
</table>

Note that, under these assumptions, summer/winter balancing would require lakes for pumped storage having a total area that is 5 per cent 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 [4, ch. 26] identifies 15 candidate locations for further pumped storage in the UK (in Scotland and Wales) and speculates that 10 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 its 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 §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 such as 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, because 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 such as 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 [4, fig. 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 per cent 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 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 (http://www.pv-magazine.com/news/details/beitrag/germany-record-40-percent-solar-weekend_100006953/#axzz2JGVmUlkA).)

For solar photovoltaics to supply 6 per cent or more of today’s average electricity demand in the UK would involve some technical challenges. The UK’s National Grid (2012, personal communication) has 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 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 its advice to me, National Grid reckoned that 40 per cent of demand at any time should be served by inertial generators, and it 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 (e.g. 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 us assume that these technical constraints can be solved. What if solar photovoltaics supplied 11 per cent 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 per cent 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 (i) large pieces of flexible demand; (ii) large interconnectors to other countries willing to buy excess electricity; or (iii) 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 per cent. 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 per cent of the delivered electricity goes via a store with a round-trip efficiency of 75 per cent, 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 h 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 five dull days would be $15 000 (which gives a total cost of $21 000, as shown in figure 12b). Assuming a working life of 20 years, electricity from the system just described would cost 12¢ per kWh; for comparison, the consumer wholesale price of electricity
Figure 11. Electricity demand in the UK and modelled solar production, assuming 40 GW of solar capacity. (a–c) The upper curves show Britain’s electricity demand, half-hourly, in 2006. The lower data sequence in (a) is a scaled-up rendering of the electricity production of a roof-mounted south-facing 4.3 kW 25 m$^2$ array in Cambridgeshire, UK, 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.) (b, c) The lower 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 10 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 photovoltaics is to contribute on average more than 11% of British electricity demand without generation being frequently constrained off, significant developments will be required in demand-side response, large-scale storage, and interconnection. (Online version in colour.)

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 figure 12a,b to read out the 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 $1 per watt including peripheral plant, but also the cost of storage needs to fall to a ballpark cost of $125 per kWh or below. The former breakthrough may be happening this decade, but the storage-cost breakthrough is not yet here, and pumped storage is unlikely to be deployable at the required scale. If 120 h (five dull days) of storage were provided for a solar farm by dedicated pumped storage, then the lake area required in a mountainous location would be about the same as the area of the solar panels in the farm. (Dinorwig, a 9 GWh pumped storage facility using a pair of lakes with a vertical separation of 500 m and a combined area of about 1.1 km$^2$, stores 8.2 kWh per square metre of lake area [4, pp. 190–193]; at a ratio of 120 kWh per average kW of solar, that implies a pumped storage area of 15 m$^2$ per kW of solar output.) Two
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 h of storage (as might be appropriate in a location such as Los Angeles); (b) 120 h 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 & Jewell [13]. Cost of pumped storage (p.s., $125 per kWh) is based on Auer & Keil [14]. 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). (Online version in colour.)

(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.

(i) Ice

The best large-scale commercial ice production has an energy intensity of 270 kJ kg$^{-1}$ (for water-cooled ice-makers) or 330 kJ kg$^{-1}$ (for air-cooled ice-makers). Figure 13 shows the mid-point, 300 kJ kg$^{-1}$ (0.083 kWh kg$^{-1}$). (Thermodynamics would allow lower energy intensities—the latent heat of fusion of ice is 333 kJ kg$^{-1}$ and the heat removal to cool water from 20°C to 0 is 80 kJ kg$^{-1}$, so the energy intensity of a freezer with a coefficient of performance of, say, 4 would be about 104 kJ kg$^{-1}$; the thermodynamic limit when the external temperature is 35°C is a coefficient of...
(ii) Ammonia

World ammonia production is 131 million metric tonnes 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.

(iii) 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 kg$^{-1}$. If hot water demand is assumed to be about 33 kg per day per person (12 000 kg per year per person), then 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
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.

(iv) Aluminium

The UK’s aluminium consumption is estimated to be about 35 kg per year per person [21]. 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 kg\(^{-1}\) (20 kWh kg\(^{-1}\)). Aluminium electrolysis at a rate of 35 kg per year per person would consume about 80 W per person.

(v) 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 per year. The International Energy Agency anticipates 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 kg\(^{-1}\) of hydrogen; in the future, new production technologies are expected to become commercial with intensities in the range 28–60 kWh kg\(^{-1}\) [22]. 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.

(vi) 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 kg\(^{-1}\) 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

\[
1 \text{ kg of gasoline} \rightarrow 13 \text{ kWh} + 3 \text{ kg CO}_2.
\]

At the limit, thermodynamics might permit this reaction to be reversed for a payment of 13 kWh kg\(^{-1}\) of gasoline, for a total cost (including ideal air-capture) of 13.4 kWh kg\(^{-1}\). Realistically, if air-capture and fuel synthesis using electricity have an efficiency of 38 per cent (or better), then the energy intensity might be 35 kWh kg\(^{-1}\) (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 2000–4500 watts per person, if today’s consumption of liquid fuels were sustained. Given how difficult it is to electrify some forms of transport (e.g. 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 per cent 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 per cent, and that methane could also be produced with an electricity-to-methane efficiency of 48 per cent [23,24]. 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 per cent. 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) [25]. If both these liquid power demands were met from electricity via processes with an efficiency of 38 per cent, then the total electrical power
Table 4. Power per unit area of a very large concentrating solar power (CSP) station, including its high-voltage transmission lines, delivering 40 GW, allowing for 10% loss in transmission. The area of Greater London is 1580 km$^2$. HVDC, high-voltage direct current.

<table>
<thead>
<tr>
<th></th>
<th>15 W m$^{-2}$</th>
<th>20 W m$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>area for 44.4 GW (average) of CSP</td>
<td>2960 km$^2$</td>
<td>2220 km$^2$</td>
</tr>
<tr>
<td>land for 50 GW (peak) HVDC power lines</td>
<td>1500 km$^2$</td>
<td>1500 km$^2$</td>
</tr>
<tr>
<td>total area</td>
<td>4460 km$^2$</td>
<td>3720 km$^2$</td>
</tr>
<tr>
<td>net power per unit area</td>
<td>9.0 W m$^{-2}$</td>
<td>10.7 W m$^{-2}$</td>
</tr>
</tbody>
</table>

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 is equal to 24 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 sounds 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 1 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 (e.g. www.desertec.org) envision a large energy contribution coming to high-consuming, high-population-density regions in 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, UK: 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 over 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 tonnes 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 United Nations Framework Convention on Climate Change 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.

I thank Katharine Hill for assistance with the collation of the data in tables 1–3, and Peter Edwards for helpful discussions.

Appendix A. Solar farm data

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


Data from one solar farm in the FRV annual report (Stornara farm, located in Ginosa, Puglia, Italy) were excluded on the grounds that the load factor implied by the predicted production (12 941 MWh yr\(^{-1}\) 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 the UK are from www.vogtsolar.co.uk and westmillsolar.coop.

References


