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

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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.

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; 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 measures 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 an energy storage solution; 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. Average power per unit area

Figure 1 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 1 is

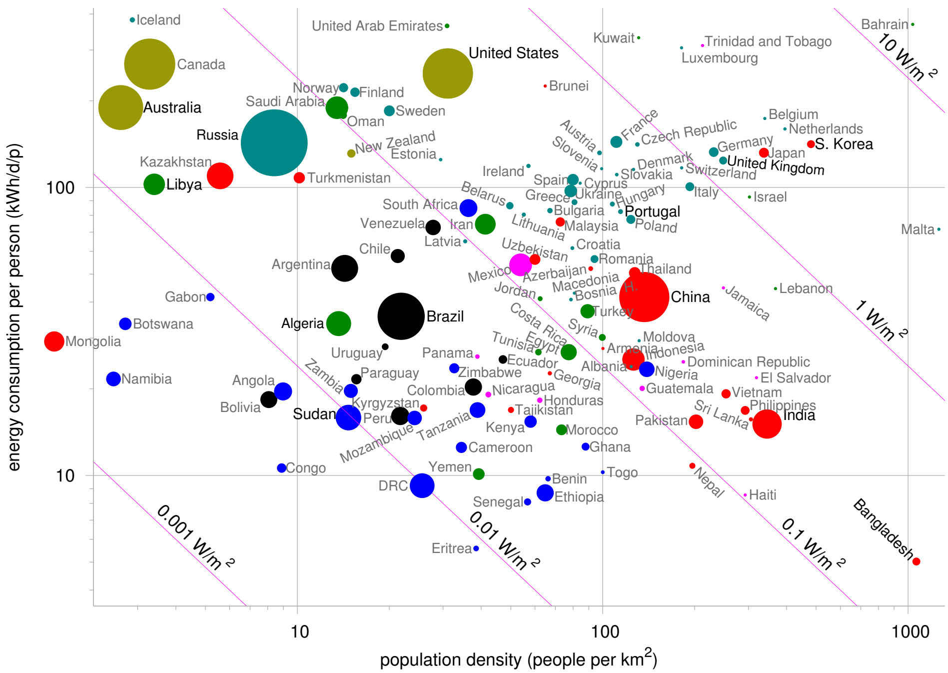


Figure 1. Power consumption per person versus population density, in 2005. Point size is proportional to land area (except for areas less than 38 000 km^2 (eg, Belgium), which are shown by a fixed smallest point size to ensure visibility). The straight lines with slope -1 are contours of equal power 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.

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 1 show data for 2005, but the world does not stand still. Figure 2 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 3 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 1–3 are straight lines with slope -1. For example, Saudi Arabia and Norway (towards the top left of figure 1), Mexico (in the middle), and Guatamala 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% of the world's population live in countries that

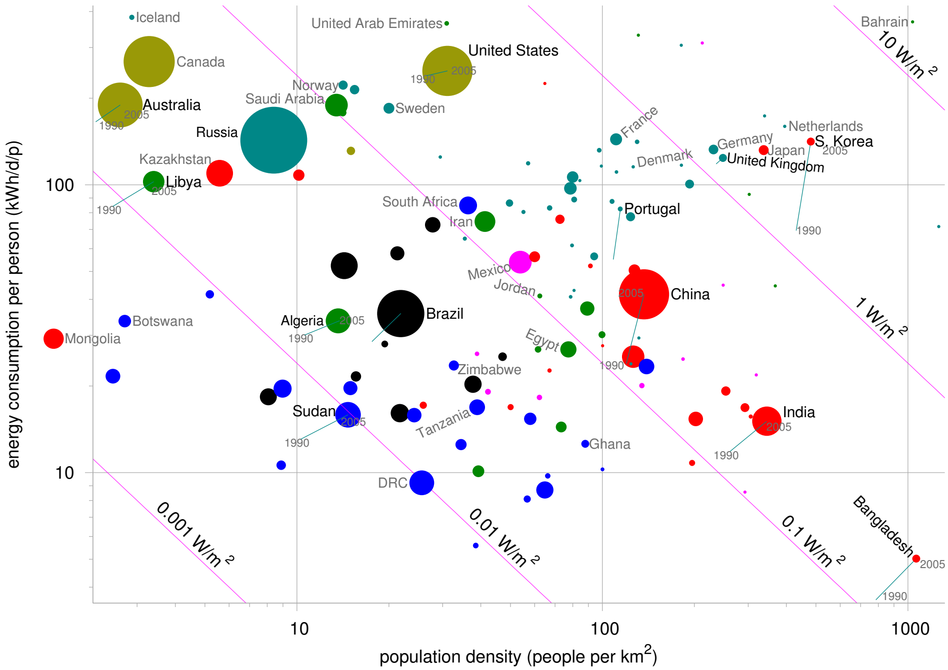


Figure 2. Power consumption per person versus population density, in 2005. Point size is proportional to land area. Line segments show 15 years of "progress" (from 1990 to 2005) for Australia, Libya, the United States, Sudan, Brazil, Portugal, China, India, Bangladesh, the United Kingdom, and S. Korea.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

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 1, have an energy consumption per unit area of 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 all 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; onshore and offshore wind farms in England and Wales deliver roughly 2.5 watts per square metre; wind farms on Scottish hilltops deliver roughly 3.5 watts per square metre [MacKay, 2012]; solar photovoltaic farms in Bavaria and Vermont deliver 4 watts per square metre (Appendix A); concentrating solar power stations in deserts might deliver 20 watts per square metre [MacKay, 2008, p. 184]. Figure 4 shows some of these renewable power densities by green contour lines, along with the country data from figure 1. (For solar photovoltaic farms, I have shown a contour line at 5 W/m^2 on the grounds that the solar farm for which I have best data, located in Vermont, where it produces 3.8 W/m^2, would probably produce 4.5 W/m^2 were it in Kansas City, 5 W/m^2 were it in Denver or Lisbon, and 6 W/m^2 were it in

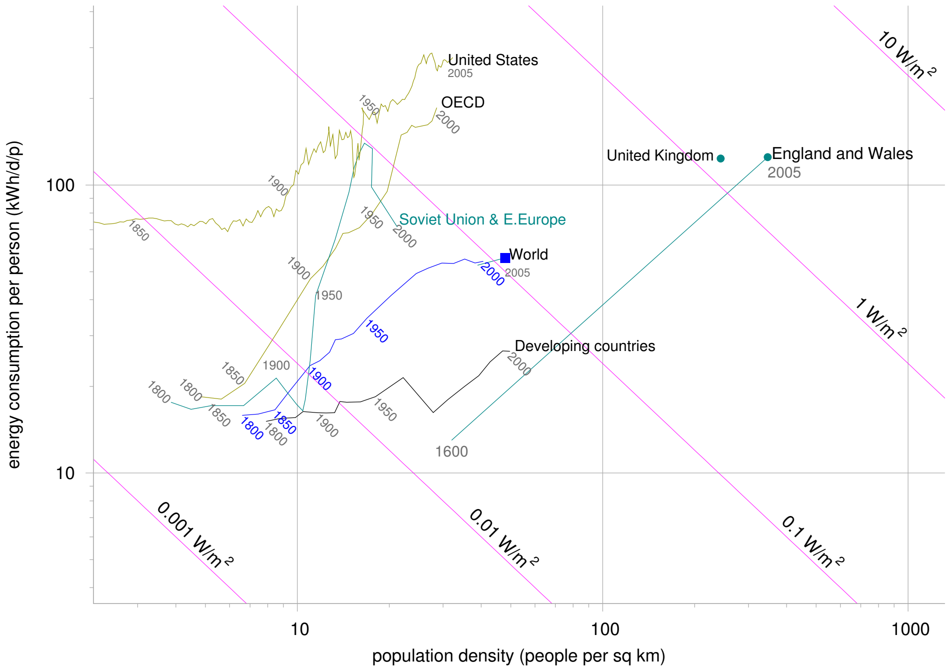


Figure 3. Power consumption per person versus population density, from 1600 or 1800 to 2005. Sources: [Grubler, 2008, Wrigley, 2010].

Los Angeles, on the basis of the insolation data in figure 5(a).) 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-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 solar cells such as 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

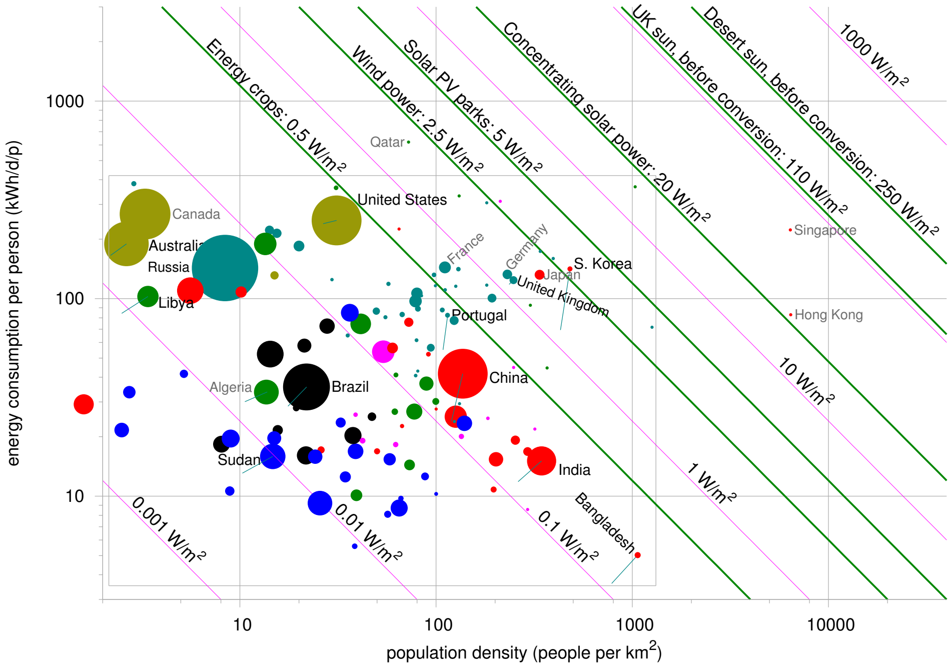


Figure 4. Power consumption per person versus population density, in 2005. Point size is proportional to land area. The diagonal lines are contours of power-consumption-per-unit-area. The grey box corresponds to the region shown in figures 1 and 2.

have much higher power densities. 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 of 740 W/m^2. Nuclear power facilities have a similar power per unit area to coal [MacKay, 2012]. The land area 'occupied' by the UK's high-voltage transmission system is somewhere between 230 km^2 and 1300 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 GW)/(57 km^2 + 230$\leftrightarrow$1300 km^2) = 146$\leftrightarrow$31 W/m^2. The Pembroke oil refinery 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.

Figure 4 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 and 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.)

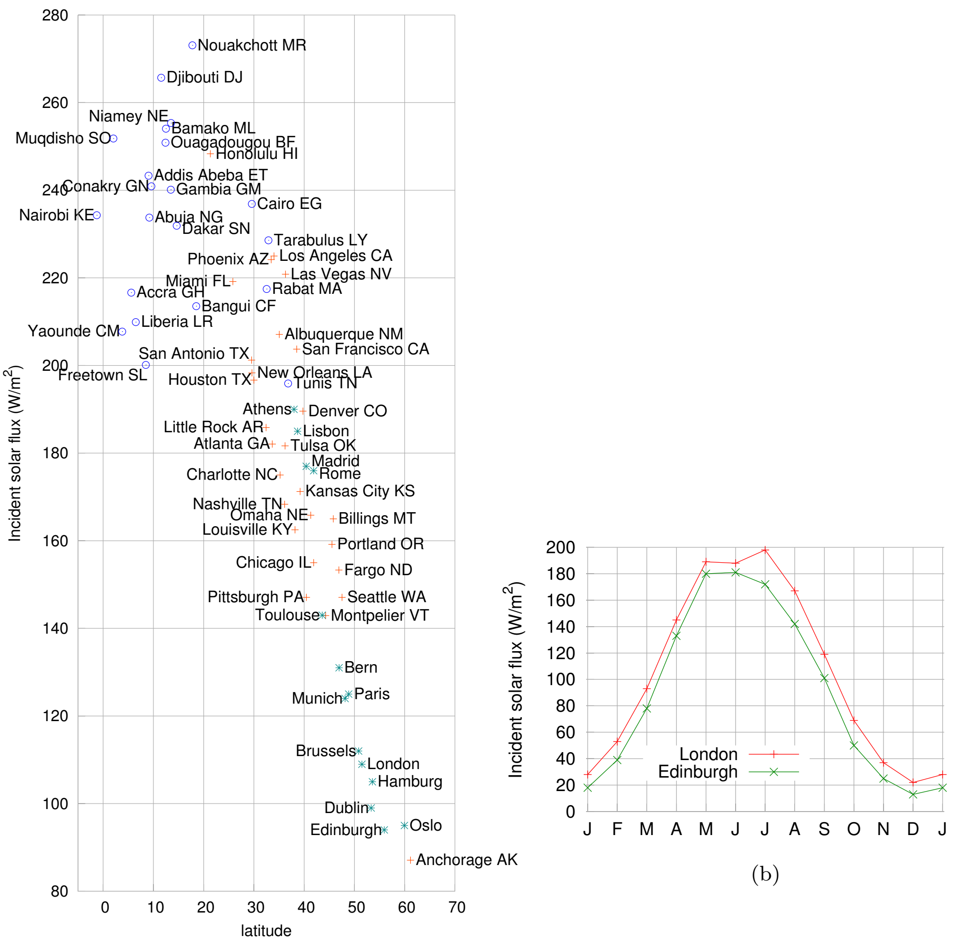
The UK Department of Energy and Climate Change has published an interactive open-source tool, the 2050 Pathways Calculator, which allows the user to explore the effectiveness for the UK of different combinations of demand-side and supply-side actions. The UK government's *Carbon Plan*, published in December 2011, illustrates the magnitude of effort required to achieve the UK's 2050 goal of 80% 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).

2. The potential role for solar

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 4–6 W/m^2, depending where it is located; and concentrating solar power in deserts may deliver about 20 W/m^2.

It is commonly noted that out of all renewables, solar power has the biggest technical potential. While this is true, 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 is slightly more than twice as great in Los Angeles as in London (figure 5a) so if solar power's costs fall so that it reaches "grid parity" in Los Angeles, its costs need to fall by roughly another factor of two to reach grid parity in England, and the area of panels required there to deliver a given average output would be doubled. 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 5b). Meanwhile, energy demand in the UK is significantly larger in winter than summer (figure 7). Moreover, in the UK, daily electricity demand has its maximum not at noon but at 6pm. Not all countries are like the UK – 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.

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 coun-



(a) (b)

Figure 5. (a) Average power of sunshine falling on a horizontal surface in selected locations in Europe, North America, and Africa. (b) Average solar intensity in London and Edinburgh as a function of time of 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/`.

try 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).

For solar photovoltaics to supply 11% or more of today's *average* electricity

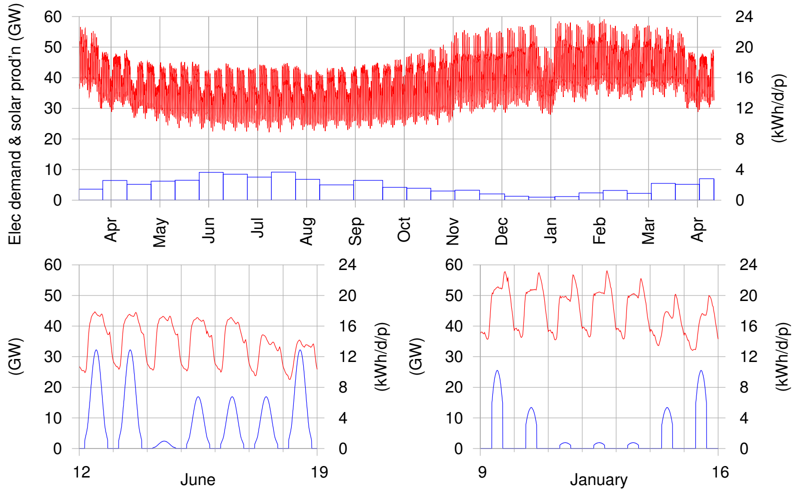


Figure 6. Electricity demand in the UK and modelled solar production, assuming 40 GW of solar capacity. In all three panels the upper red curves show Great Britain's electricity demand, half-hourly, in 2006. The blue data in the upper panel are a scaled-up rendering of the electricity production of a 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 roof 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.

demand in the UK would involve technical challenges. As figure 6 shows, a fleet of 40 GW of solar panels in the UK (670 W of capacity per person), whose average output (4.4 GW) would equal 11% of current electricity demand, would occasionally have a total output close to the total electricity demand; at these levels of solar capacity, peaks of solar output would cause either baseload electricity generators or solar generators to be constrained off, 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.

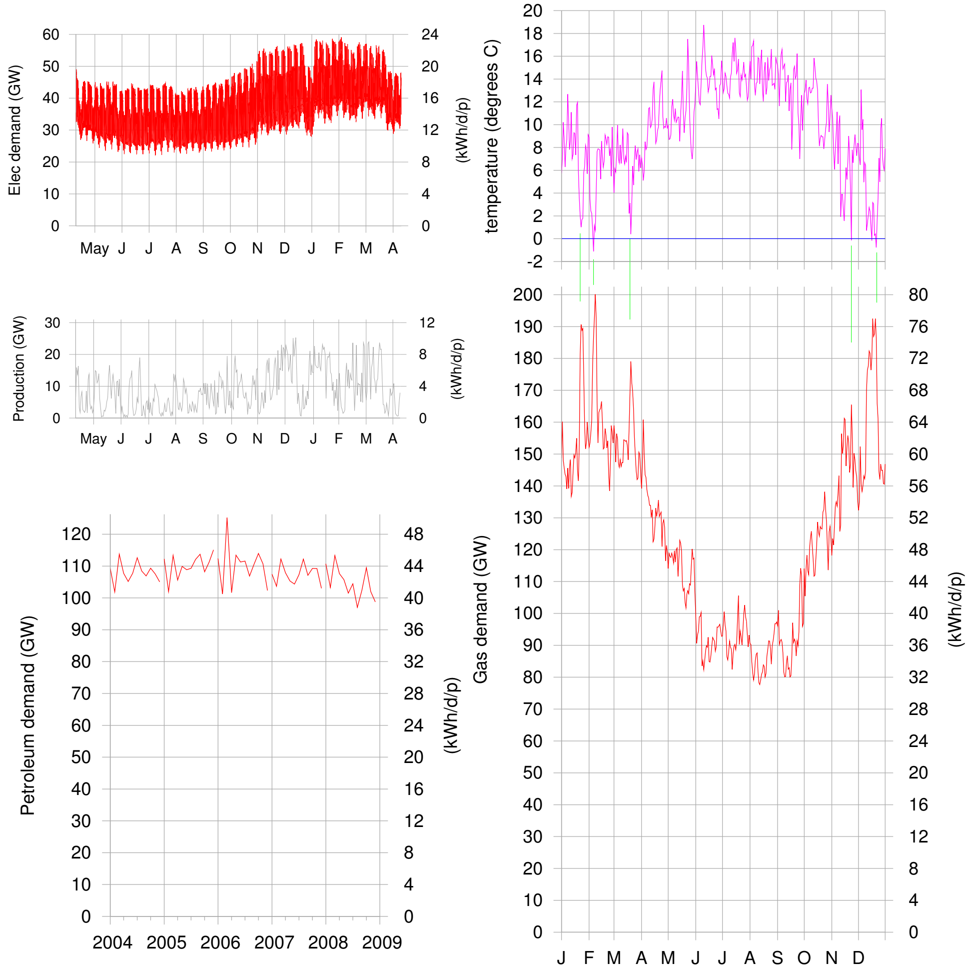


Figure 7. Electricity, gas, and transport demand; and modelled wind production, assuming 33 GW of capacity, all on the same vertical scale. Wind production is modelled by scaling data from Ireland.

(*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 8 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 calculation and assumptions 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

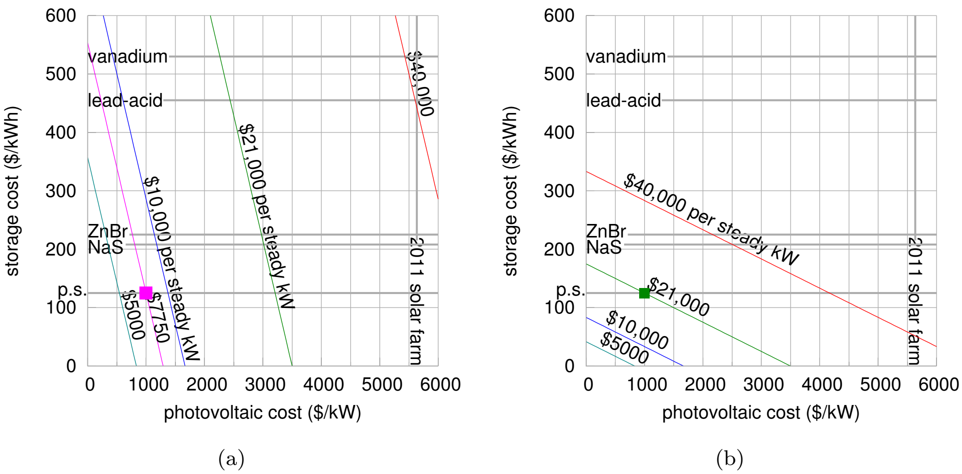


Figure 8. Contour plot of the total cost of a photovoltaic system, in a sunny location, capable of giving a steady 1-kW output with (a) 14 hours of storage (as might be appropriate in a location such as Los Angeles); (b) 120 hours of storage (as might be appropriate in cloudier locations), as a function 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 (Appendix A), 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).

$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 8a). 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 8b). 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. 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. If 120 hours 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 and reversible thermal storage using high-efficiency heat pumps.

(*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. (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 chemicals (ice, ammonia, hot water, aluminium, hydrogen, and gasoline), figure 9 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 chemical, in kg per year per person. The contours show how much electrical power, in watts per person, would be consumed by producing each chemical 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 9 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 9 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 9, I assumed 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 En-

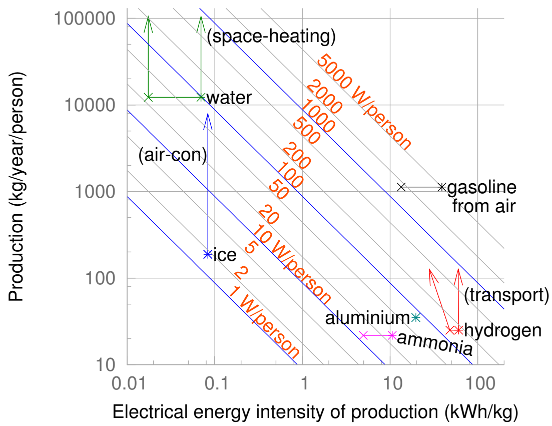


Figure 9. Contour plot of potential average consumption of electrical power as a function of production and energy-intensity of storable materials. The points show these two properties for six materials: ice, ammonia, aluminium, hot water, hydrogen, and gasoline from thin air. Where there are two points, 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.

glish 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.

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 9: 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 9 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 projected electricity consumption for hydrogen production is roughly 500 W.

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 1. *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.*

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 kg of gasoline $\longrightarrow$ 13 kWh + 3 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 13.13 kWh per kg. Realistically, if air-capture and fuel synthesis using electricity have an efficiency of 34% or so, then the energy intensity might be 39 kWh per kg. For the per-capita production in figure 9 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 5000 watts per person.

(*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 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 1 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, the land area of the solar power station in the desert might need to be increased, 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

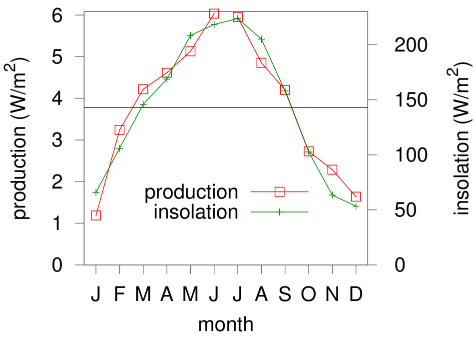


Figure 10. Electricity production from AllEarth Renewables Solar Farm, 350 Dubois Drive, South Burlington, Vermont, during the last 6 months of 2011 and the first 6 months of 2012; and insolation (10-year average) for Montpelier (33 miles away from the farm) from the NASA Surface meteorology and Solar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

not new. In the 1890s, ice houses were a common sight, and Norway exported 340 000 tons of ice to England each year.

3. 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. 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.

Appendix A. 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 peak capacity of 2.1 MW. The farm's land-area is 0.1 km^2. Figure 10 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 very 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%.

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