Visualizing Sustainable Energy for the USA

David J.C. MacKay

Let's express energy consumption and energy production using simple personal units. The units I'll use are kilowatt-hours. One kilowatt-hour (kWh) is the energy used by leaving a 40-watt bulb on for 24 hours. The chemical energy in the food you eat to stay alive amounts to about 3 kWh per day. Taking one hot bath uses about 5 kWh of heat. Driving an ordinary car (delivering 25 miles per US-gallon) 100 km uses 80 kWh of fuel.

Americans use a total of **250 kWh per day per person** for transport, heating, manufacturing, electricity, and so forth. That's equivalent to every person having 250 lightbulbs switched on all the time. And, as figure 1 shows, most of this energy today comes from fossil fuels. Roughly 81 kWh per day (kWh/d) per person of fossil fuels and 22.5 kWh/d of nuclear heat go into making electricity. When wind, solar, and hydroelectricity are added, the total electricity delivered is 37 kWh/d. We use a further 44 kWh/d of natural gas and 105 kWh/d of oil for heat, for chemical processes, and for transport. Geothermal sources and biomass contribute smaller amounts.

What are our post-fossil-fuel options? We can match supply to demand in two ways: by energy-saving and by increasing non-fossil-fuel sources of energy-supply.

Among the **energy-saving** options, two promising technology switches are (a) electrifying transport (electric vehicles can be about four times as energy-efficient as standard fossil-fuel vehicles) and (b) using electric-powered heat pumps to deliver winter heating and hot water. (Heat pumps can be three or four times as energy-efficient as standard heaters.) We can also save energy by making vehicles lighter; by insulating buildings better; by improving the engineering of appliances such as refrigerators and air-conditioners; and by enhancing consumers' understanding of their consumption through engaging energy-meter-displays.

Among all the **energy-supply** technologies, the four with the biggest potential today are solar power, wind power, bio-energy, and nuclear power. Figure 2 visualizes, for illustration, the sizes of solar, wind, bio-energy, and nuclear facilities that would each supply **42 kWh per day per person**. (Remember, the total power consumption today is six times as big – 250 kWh per day per person. I picked 42 kWh per day per person from each source on the grounds that, if some energy-saving measures are introduced, roughly three or four times 42 kWh per day per person might be enough to maintain today's lifestyle. I am not recommending this particular energy mix; I picked equal amounts from each source so as to make it easy to see the exchange rates, and easy to construct alternative mixes.)

- To supply 42 kWh per day per person from solar power (for everyone in the USA) requires concentrating solar power stations with total area equal to one eighth of Arizona. This area is shown on the map by 21 hexagons, each with an area of 1650 square kilometres (twice

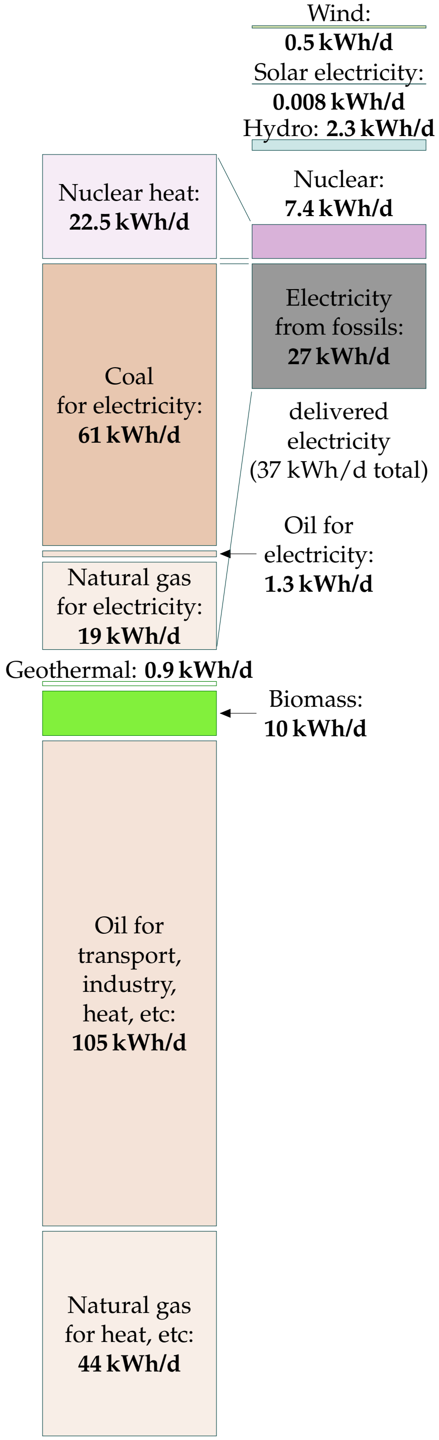


Figure 1. Current consumption per person in the USA is about 250 kWh per day. The first column shows the **chemical** and **thermal** sources of power, some of which are converted to electricity; the second column shows the breakdown of the electricity, a little of which comes from **mechanical** and **solar** sources.

the area of San Diego) and an average output of 25 GW. [This visualization assumes that concentrating solar power stations can deliver an average power per unit area of about 15 W/m^2.]

- To deliver 42 kWh per day per person from wind would require wind farms with a total area roughly equal to the area of California (ten New Jerseys) – a one-hundred-fold increase in US wind power over 2008 levels. [Windfarms deliver roughly 2.5 W/m^2.]
- To get 42 kWh per day per person from bio-energy would take roughly 10% of US land area (fifty New Jerseys), assuming energy crops have a power per unit area of 0.5 W/m^2. This chemical energy could replace some of today's oil and natural-gas consumption.
- To get 42 kWh per day per person from nuclear power would require 525 one-gigawatt nuclear power stations – a roughly five-fold increase over today's levels.

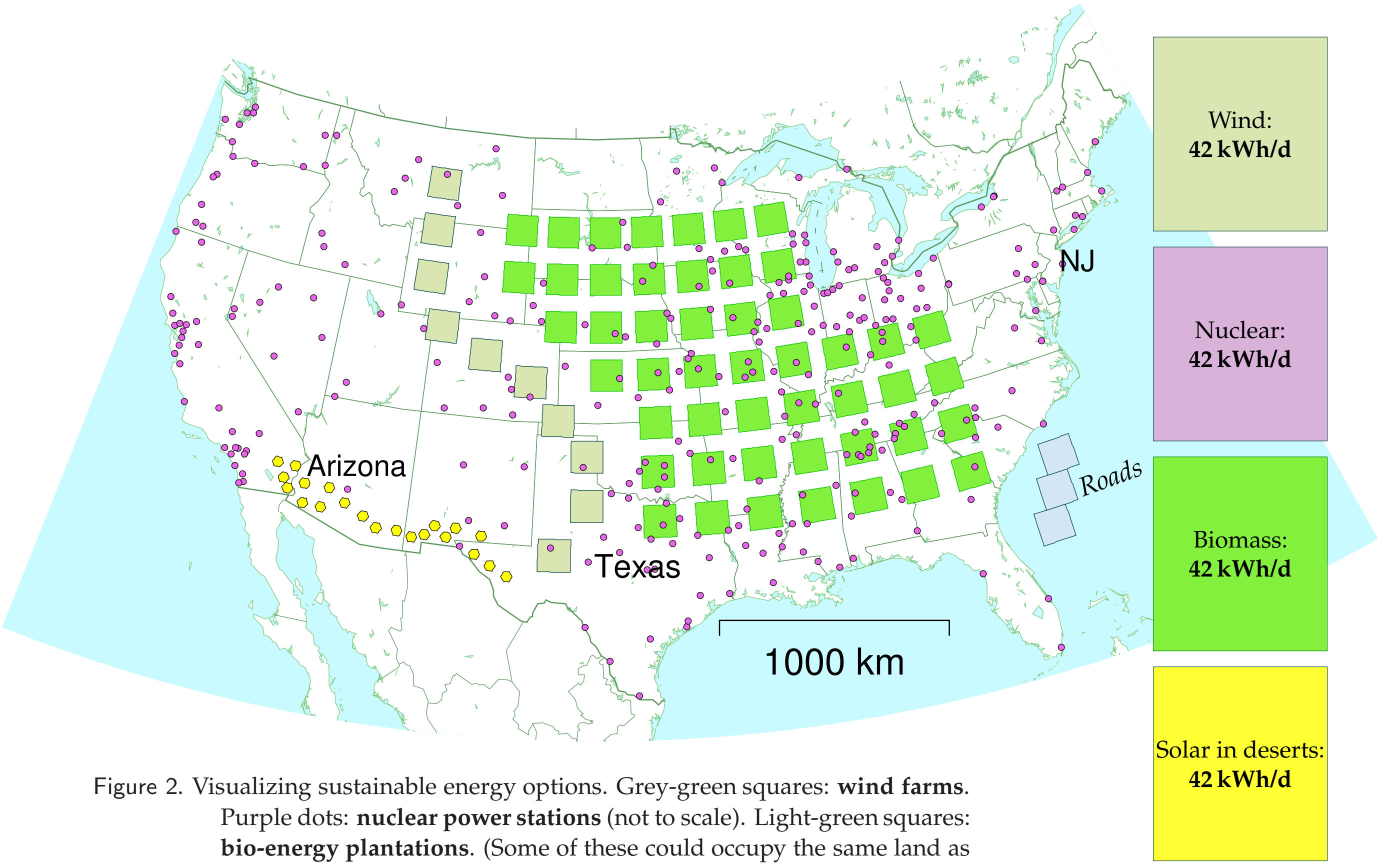


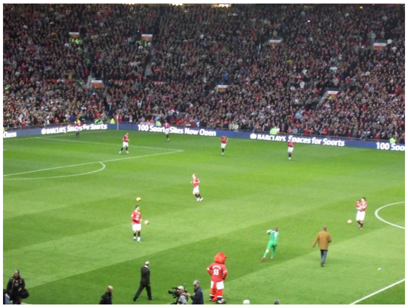
Figure 2. Visualizing sustainable energy options. Grey-green squares: **wind farms**. Purple dots: **nuclear power stations** (not to scale). Light-green squares: **bio-energy plantations**. (Some of these could occupy the same land as the wind farms.) Yellow hexagons in the southwest: **concentrating solar power facilities in deserts**, to scale. For comparison, the blue-grey squares in the Atlantic show the total area devoted to **roads** in the USA.

Photos by `eSolar.com`

Let's re-visualize these national numbers in personal terms. What would individuals or communities need to do?

- To obtain 42 kWh per day from solar power, each person requires either roughly 80 square metres of solar photovoltaic panels, or a share of a concentrating solar power station. One person's share would be 30 mirrors, each one square metre in size, and a one-four-hundredth share of a solar collector tower.
- We can get 42 kWh per day per person from wind (on average) if every 300 people have one 2-MW turbine.
- To get 42 kWh per day from bio-energy, each person needs the output of 1 acre (4000 square metres) of land – that's half a football field.
- To get 42 kWh per day per person from nuclear power, each city the size of Denver, Boston, Las Vegas, and Portland needs its own one-gigawatt nuclear power station, occupying about one square kilometre. Bigger cities would have proportionally more – 7 for Los Angeles, 5 nukes for Chicago, and 4 nukes for Houston, for example.

I hope these numbers convey the scale of action required to put in place a sustainable energy solution.



Of course there are other technologies I haven't mentioned in this short note, which can also contribute to a plan that adds up. Home-mounted **solar hot water panels**, for example, can easily deliver at least half of the hot-water demand of a typical family in almost all climates; **seasonal heat storage systems** might allow excess heat to be harvested in the summer and stored until the winter; proponents of **enhanced geothermal systems** have estimated that, with investment, geothermal resources in the US could deliver at least 100 GW of electricity – in personal units, that's 8 kWh per day per person; and **clean coal** and **clean gas with carbon capture and storage** are crucial technologies to reduce the risks associated with fossil-fuel burning – roughly 22 kWh per day per person of low-carbon electricity could be delivered if all US fossil-fuel-burning power stations were converted to perform carbon capture and storage. And finally, we may wish to keep on the table the option of **lifestyle changes that reduce energy consumption**, for example switching from car-driving to public transport, cycling, and walking; flying less; and buying less stuff.

It's not going to be easy to make a energy plan that adds up; but it is possible. We need to make some choices and get building.

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Sustainable Energy – without the hot air

David J.C. MacKay

This remarkable book sets out, with enormous clarity and objectivity, the various alternative low-carbon pathways that are open to us.

Sir David King FRS
Chief Scientific Adviser to the UK Government, 2000–08

For anyone with influence on energy policy, whether in government, business or a campaign group, this book should be compulsory reading.

Tony Juniper
Former Executive Director, Friends of the Earth

MacKay's book shows how, when it comes to energy, you too can do the simple arithmetic and learn the simple scientific facts needed to work out what energy you need and where it might come from.

Prof David Mumford
Professor of Applied Mathematics, Brown University
Member of the US National Academy of Sciences

Common sense, technology literacy, and a little calculation go a long way in helping the reader sort sense from nonsense in the challenges of developing alternatives to fossil fuels. MacKay has provided a high priority book on a high priority problem.

Professor William W. Hogan
Raymond Plank Professor of Global Energy Policy
John F. Kennedy School of Government, Harvard University

This is a complete resource for assessing the many options for choosing between different energy options and for using energy more efficiently. Teachers, students, and any intelligent citizen will find here all the tools needed to think intelligently about sustainability. This is the most important book about applying science to public problems that I have read this year.

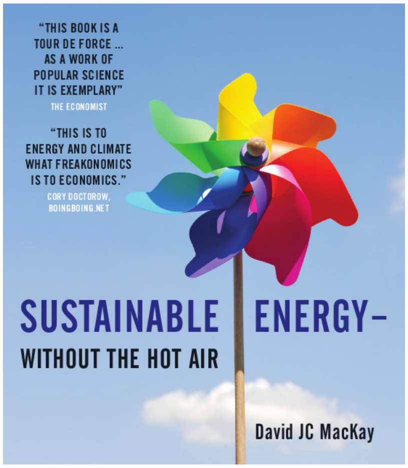
Prof Jerry Gollub
Professor of Physics, Haverford College and University of Pennsylvania
Member of the US National Academy of Sciences

MacKay's book is the most practical, solidly analytical, and enjoyable book on energy that I have seen. This heroic work gets the energy story straight, assessing the constraints imposed by physical reality that we must work within.

Prof Tom Murphy
Associate Professor of Physics, UC San Diego

This book is a tour de force . . . As a work of popular science it is exemplary.

The Economist



"Sustainable Energy – without the hot air" was published in hardback and paperback by UIT Cambridge on 2nd December 2008 in the UK, and on 1st May 2009 in North America. The book is also available for free online at `www.withouthotair.com`.

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