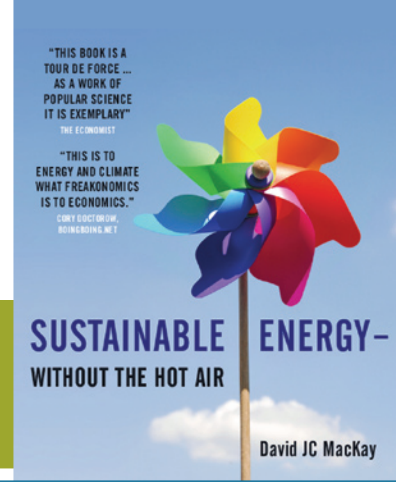
Sustainable Energy—Without the Hot Air

The statistics thrown around in the sustainable-energy debate are often chosen to impress rather than inform. "Los Angeles residents drive 142 million miles—the distance from Earth to Mars—every single day." Sometimes there are no numbers at all, just adjectives: "We have a *huge* amount of wind energy just waiting to be tapped." But how does that "huge" compare to the hugeness of our energy consumption?

David MacKay (PhD '92), the Chief Scientific Advisor to the United Kingdom's Department of Energy and Climate Change, has done the math. He offers a simple, common-sense analysis that answers such questions as, "Can the U.S. live on its own renewable energy sources?" and "If everyone turns off their cell-phone chargers when not in use, will an energy crisis be averted?"

MacKay at the Houses of Parliament with the most efficient form of personal transportation ever developed. It uses just one kilowatt-hour (derived from biofuels!) per 100 person-kilometers—80 times better than a car.



By David MacKay

I'll take it as given that we're motivated by at least one of three compelling reasons to stop using fossil fuels. First, easily accessible fossil fuels are a finite resource; at some point, that resource will run out. Second, setting fire to fossil fuels puts out carbon dioxide—a vast geoengineering experiment with a very uncertain outcome. Third, even if you don't believe in climate change and even if *global* fossil fuels aren't going to run out today, maybe *your* fossil fuels are running out; so if you don't want to depend on other people for your energy, you might want to get off fossil fuels.

A lot of people get emotional about our energy options, but emotions alone will not get us where we need to go. I think it's important to have some numbers in the conversation, if we're going to have a constructive debate about energy options.

To make our supply and demand options comprehensible and comparable, I suggest measuring all forms of energy in one set of units, rather than switching between barrels of oil, terawatt-hours, and petajoules. To avoid having answers that involve incomprehensible millions or billions, I will estimate all energy and power figures *per person*. My rough guide to sustainable energy will measure energy in kilowatt-hours, and power—the rate of using or producing energy—in kilowatt-hours per day. By measuring powers in kilowatt-hours per day (rather than watts or kilowatts), it's clearer we're talking about a *rate* of energy consumption. I'll deliberately use rough, back-of-the-envelope numbers to streamline the calculations and permit fluent thought.

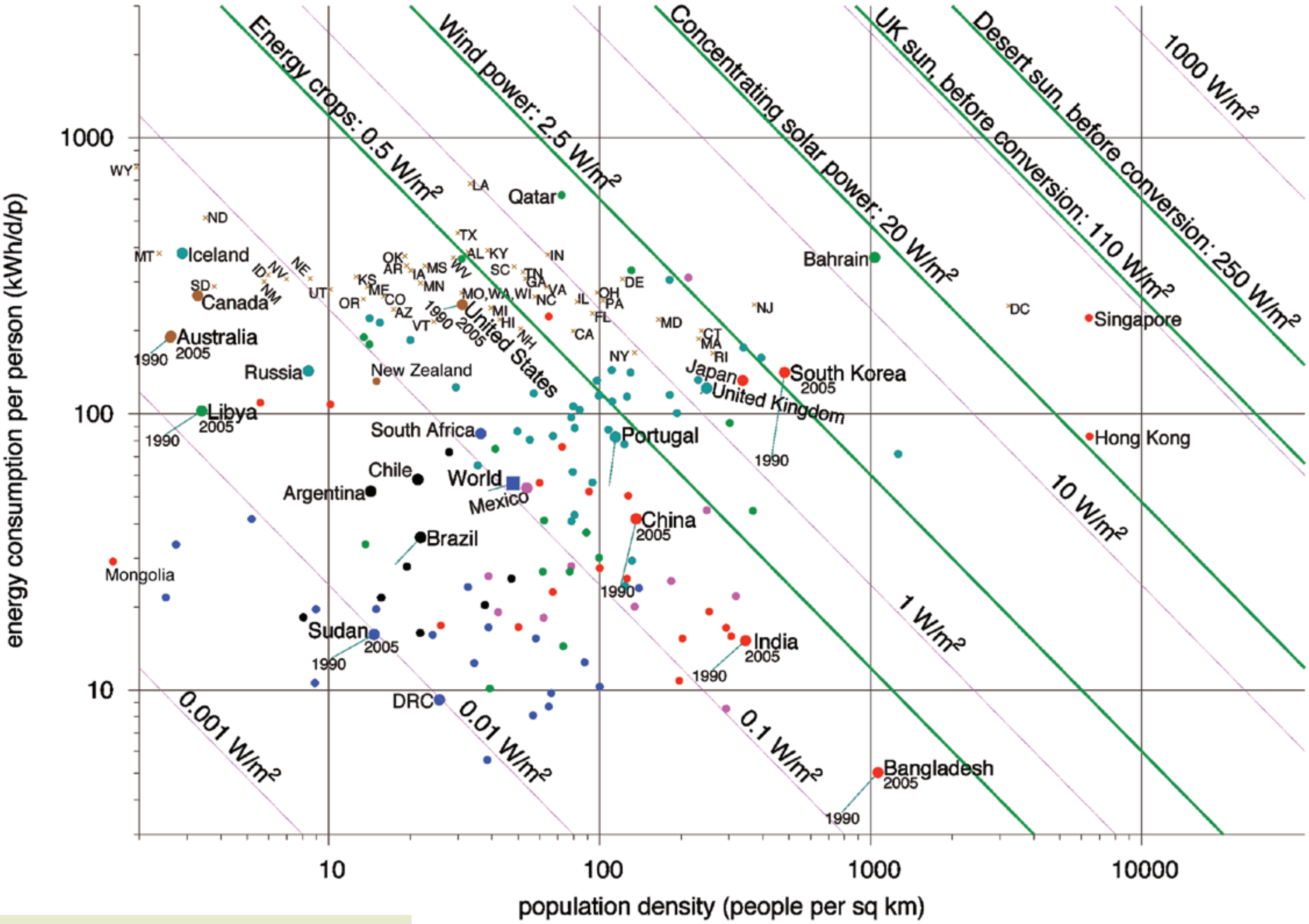
Everyday personal choices come in small numbers of kilowatt-hours. If you burn one 40-watt lightbulb for 24 hours, you use one kilowatt-hour of electricity, and it might cost you 10 cents. The chemical energy in the food you eat amounts to about three kilowatt-hours a day. If you take a hot bath, that's five kilowatt-hours of energy to heat the water. If you drive an average American car that gets 25 miles to the gallon on a trip of 100 kilometers, you use 80 kilowatt-hours of chemical energy. If you fly from London to Los Angeles and back, you use 10,000 kilowatt-hours—an incomprehensibly large number—but if you fly only once a year, your average power consumption comes out to 26 kilowatt-hours per day. And if you have a typical three-bedroom American house, you might be using 80 kilowatt-hours per day all told to run it. Share this between a family of three, and we're back down into the 25 kilowatt-hours per day ballpark.

These simple, easy-to-grasp numbers can be our lifeboat on the flood of crazy, innumerate codswallop that inundates us daily from all sides of the energy debate. For example, a 2007 ad campaign said that if every London household unplugged their cell-phone chargers when not in use, we could prevent 31 *thousand* tons of CO_2 from getting into the air a year. Sounds like these black, planet-destroying objects are about as evil as Darth Vader. But let's just check the numbers: a cell-phone charger left plugged in uses about half a watt, so the energy saved by switching it off for a whole day is 0.01 kilowatt-hours, which is exactly equal to the energy used by driving an average car for one second. I'm not saying don't switch it off, but perhaps when we're trying to make a plan that adds up, cell-phone chargers should be some way down on the list of priorities for public information campaigns.

The total energy consumption of the United States divided by the nation's population is 250 kilowatt-hours per day per person. (Britain and the other European countries use half that amount, 125 kilowatt-hours per day per person. Australia and Canada use about 300.) You can think of this as every American having 250 40-watt lightbulbs burning all the time. One kilowatt-hour per day is also the approximate power output of a human servant, so it's as if, in the modern age, we each have 250 mechanical servants on staff. This energy goes into transportation, into heating and air conditioning, into electricity, and into the making, distribution, and ultimate disposal of *stuff*—soda cans, sweat socks, patio furniture, the latest techno-gadget, and even this magazine. There are other uses of energy, too, but the big three forms of consumption that you need to focus on for a quick conversation about energy options are transportation, heating, and electricity.

RENEWABLE ENERGY SOURCES

Most forms of renewable energy involve doing something on an area of land; to understand how easy it would be to live mainly on renewables, we need to talk about their power production per unit area and compare it with our power consumption per unit area. If we plot the number of people per square kilometer against the energy consumption per person, as shown at the top of the next page, we can read off the power consumption per unit area for a given country, state, or region. The world's average power consumption is 0.1 watts per square meter. The United Kingdom consumes about 10 times that, 1.25 watts per square meter, and America is at about



Above: Plotting population density versus per-person energy consumption gives us power consumpion per unit area. (The turquoise dots are the European countries.)

At the top left are places with very low population density and very high per-capita consumption, like Iceland. Top right, Bahrain consumes as much energy per person as Iceland, but has more than 100 times the population density. Bottom right, Bangladesh has the same population density as Bahrain, but uses only five lightbulbs per person, nearly 100 times less. A lot of countries, especially in Africa, used to be down at the bottom left, but they're all rushing up and to the right, as is the world average. This is shown by the tails on some of the dots, which track population and consumption growth from 1990 to 2005.

Both axes are logarithmic, so we can draw diagonal lines (green) to show how much power per square meter various forms of land-intensive renewable energy can produce. If a dot lies below and to the left of a green line, that energy source could meet all of that country's needs, and the distance between that dot and the line gives one an idea of how much land would be left over to live on, plant crops on, and so forth.

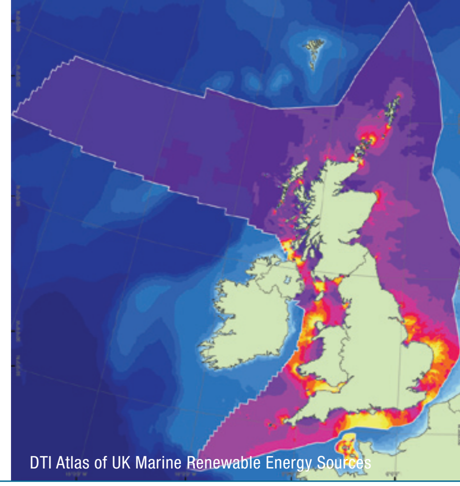
0.3 watts per square meter. Renewable energy sources also come in watts per square meter, so we can put them on the same plot and see how they compare.

Wind power, for example, offers an average of 2.5 watts per square meter for good, windy locations in Europe. That is twice the power consumption per unit area of the United Kingdom, so if you ask, "Can Britain power itself completely on wind?" the answer is, "Yes, if half the area of the U.K. is occupied by wind farms."

Energy crops deliver about half a watt per square meter in European climates, so if you covered the whole of the U.K. with energy crops, you wouldn't match today's power consumption. On the other hand, the U.S. could cover itself with energy crops and match its consumption with a little bit to spare. So there are different messages for different countries. In the tropics, by the way, temperatures are warmer and plants are more productive, so you might get perhaps 1.5 watts per square meter in Brazil.

All renewables are in the same ballpark. Rooftop solar panels in Britain deliver about 20 watts per square meter; in sunnier countries perhaps you could get double that. But rooftops are relatively small, so even if you covered every south-facing roof in Britain with solar panels, they would only deliver about five lightbulbs of power per person. If you want to get up to the scale of our actual consumption, you have to go a bit crazy and coat the countryside with solar panels, too. But there will be gaps between the solar panels, so the net power output is about five watts per square meter—twice as good as a wind farm, but still, if we wanted to match Britain's power consumption this way, we'd need solar farms roughly one quarter the size of the country. Tidal pools come out about the same as wind power, offering roughly three watts per square meter. So, again, to match today's consumption, you'd need a tidal pool the size of a country—and God in His wisdom, when He created the British Isles, provided precisely such a facility. It's called the North Sea. The North Sea is a natural tidal pool, in and out of which, and around which, great sloshes of water pour every 12 hours. If we put huge underwater windmills where the currents are big we could get something like eight watts per

Courtesy of SunPower Corporation



DTI Atlas of UK Marine Renewable Energy Sources

Far left: A traditional Bavarian farming method as practiced near Mühlhausen, Germany.
Left: The tidal-driven current flows in the areas shown in yellow on this map are capable of producing eight watts per square meter.

square meter of underwater windfarm, which could make a significant contribution to powering the U.K. However, this is a rather uncertain figure because we don't have any underwater wind farms yet, just a couple of prototypes.

If you deploy arrays of lenses or mirrors in the desert, and use them to concentrate sunlight onto collectors, you can get up to 15 or 20 watts per square meter of land area, according to the manufacturers of such arrays. Below right is an individual concentrator that will, on average, deliver 140 kilowatt-hours per day—a bit more than what's needed to power the lifestyle of the German woman standing beside it.

The key lesson is that all renewables are diffuse, and if you want them to make a significant contribution compared to today's consumption, the renewable-energy facilities have to be country-sized. And this presents problems, because while some people love the idea of harvesting renewable energy by dotting the landscape with windmills or solar panels, many don't want such things in their backyards.

So how can we make an energy plan that adds up? Perhaps we could reduce demand. Do we really *need* 125 or 250 lightbulbs' worth of power per person? One way to reduce demand would be to change our lifestyles. I used to give energy talks that recommended lifestyle change, but they did not always go down well with audiences, so my strategy now is to just be the numbers guy: I don't make any recommendations, except that, whatever choices we make, the numbers must add up. So let's take the question of lifestyle change and leave it to one side; we can come back to it again later on, if we want. There's a second way to reduce demand: technology! We are at Caltech, after all. Let's use technology that's more efficient, reduce demand by being smart, and then figure out what needs doing on the supply side.

Wind power offers an average of 2.5 watts per square meter, so if you ask, "Can Britain power itself completely on wind?" the answer is "Yes, if half the area of the U.K. is occupied by wind farms."

THE DEMAND SIDE

I'll start with transportation. Standard petrol and diesel engines are only about 25 percent efficient at turning chemical energy into oomph. In contrast, electric vehicles convert chemical energy in the battery into oomph at the wheels with an efficiency of 85 or 90 percent. Electric vehicles use only about 20 kilowatt-hours per 100 kilometers. That's about four times better than a standard fossil-fuel vehicle, which uses 80 kilowatt-hours per 100 kilometers. Of course, if you get your electricity by burning chemicals at a power station with an efficiency of only 30 percent or so, this isn't helping very much. But there are other ways to make electricity; if we transform our electricity-generating system, electric vehicles may help us make a plan that adds up.

Left: PS10, a solar concentrator plant near Seville, Spain, uses a field of mirrors to focus sunlight on a tower to heat water that spins a turbine to generate electricity. This facility generates about 5 watts per square meter of land area, on average.
Right: The 5,760 lenses in Amonix's solar array focus sunlight onto individual photovoltaic cells. At 140 kilowatt-hours per day, it could match the average energy consumption of one European or half an American.

Right: In Japan, caped crusaders Tankman and Pumpu are here to save the day. And yes, the name of the system really *is* Eco-Cute. "Kyuto" in Japanese means "to provide hot water." Far right: The actual hardware provides domestic hot water as well as heating the house.

As a transition to electric vehicles we could drive plug-in hybrid cars, which are electric vehicles that you can recharge overnight from a wall outlet. Plug-in hybrids mainly work like electric vehicles, but they have a small emergency fossil-fuel engine on board to extend the vehicle's range. When running on electricity, the Chevy Volt is expected to use 25 kilowatt-hours per 100 kilometers, which is still a big win, as long as we have somewhere satisfactory to get the electricity from.

Now let's talk about heating. In winter, you can reduce the heat loss from your house with an amazing technology called a thermostat. You grasp it, you rotate it to the left, and it will, if you turn it down one degree centigrade, reduce the heat loss by 10 percent in a typical British house. Turn it down five degrees, and you'll get a 50 percent saving in the power required to heat the house. Tinkering with thermostats is crucial. The standard thermostat keeps a building obsessively at one temperature, but humans don't want a particular temperature. If you have just cycled home on a freezing cold night and you come into a building that's only 13 centigrade rather than the 20 centigrade that many people now think is essential, it feels really warm—at least for an hour or two, and, if you're only going to be in the building that long, there's no need to heat it. Just putting the thermostat on a clock isn't enough. We need to know if there is anyone in there, and do they feel cold?

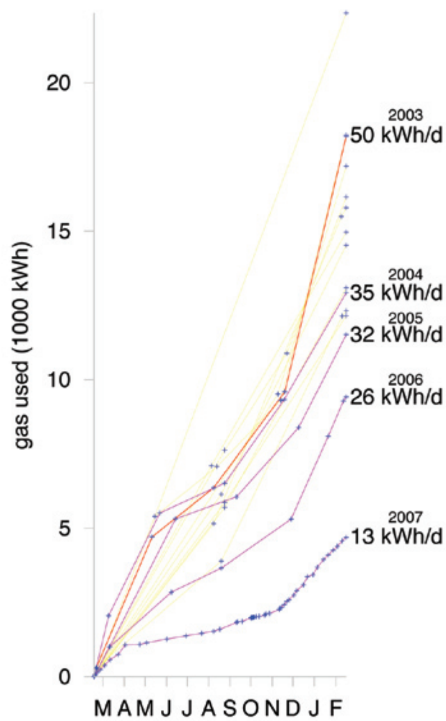
Another option is more efficient heat creation. One standard way of making heat is to set fire to natural gas, at an efficiency of about 90 percent. This sounds pretty good, but it's actually really lousy, because you're taking high-grade chemical energy and turning it into low-grade heat.

We can deliver low-grade heat with far greater efficiency with a heat pump, which is a back-to-front refrigerator. Your fridge is cold inside because it moves heat from where the food is out to the grill on the back. Take the door off the fridge, put the open fridge in the kitchen window, and it will cool down the garden. But it's still warming the kitchen, where the grill is.

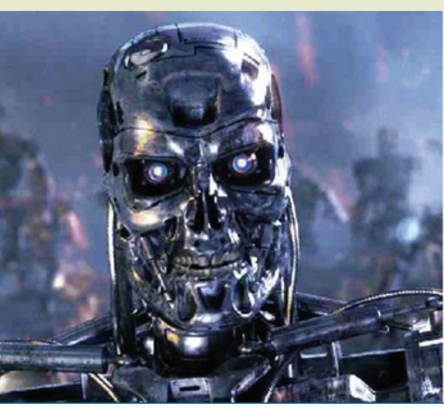
In Japan they've recognized the importance of heat pumps for decades, and the results are wonderful. According to the manufacturers, you give Pumpu (above) one kilowatt-hour of electricity, and he'll deliver 4.9 kilowatt-hours of heat by moving it from the garden into the kitchen and into Tankman. Not 90 percent efficiency, but 490 percent efficiency! So trading in all our natural-gas furnaces for electrically powered heat pumps would make a huge difference.

But the single most significant energy-saving technology is called "Read Your Meters!" Here's how it worked for me. When I started writing my book on energy, a friend asked me, "So, how much energy do you actually use?" I was embarrassed that I didn't know the answer, so I started reading my gas and electricity meters every week, and the answer completely changed. I used to use 40 or 50 kilowatt-hours per day of natural gas, and I got that down to 13 kilowatt-hours per day. Similarly, my electricity consumption went down from four kilowatt-hours per day to two kilowatt-hours per day. It's a video game, really—you want to beat last week's score, and so you try experiments.

I switched off not only the phone charger (haha), but also the DVD player, the stereo, the cable modem, all those devices that draw juice even when they're just sitting idle.



Plug-in hybrids, like the soon-to-be-released Chevy Volt, may provide a useful transitional technology on the way to all-electric vehicles. I'm not sure why they have to look like killer robots from the future.



In general, you can reduce the heat loss from your house with an amazing technology called a thermostat. You grasp it, you rotate it to the left, and it will, if you turn it down one degree centigrade, reduce the heat loss by 10 percent in a typical British house. Tinkering with thermostats is crucial.

I saved one kilowatt-hour per day, which is worth having. It's one percent of the average European's footprint. It also saved me 45 pounds a year—which I can spend on an extra holiday in the Canary Islands! This brings me to Jevons's paradox, which says that when you develop a new, more energy-efficient technology, you may well end up using more energy overall. I don't know an easy way around Jevons's paradox, but we'll have to bear it in mind as we pursue technological fixes.

THE SUPPLY SIDE

Even with these efficient technologies reducing demand, we'll have to broaden our supply options in order to make a plan that adds up. For many countries, renewables alone simply won't be enough.

One supply option is called "clean coal with carbon capture and storage," which means let's carry on using fossil fuels, but do something smarter with the carbon dioxide. The plan would be to pump CO_2 into the ground, where we intend it to stay for thousands of years; this technology has yet to be demonstrated at scale.

We could use nuclear power, which has popularity problems. Nuclear waste is nasty stuff. I don't want it in my pocket, but the wonderful thing about it is that it *would* actually *fit* in my pocket. The volume of British nuclear waste generated per person each year would almost fit in a wine bottle. The low-level waste is 760 milliliters, the intermediate-level waste is another 60 milliliters, and the 25 milliliters of high-level waste would be the sediment at the bottom of the bottle. So it's a nasty problem, but I think it's solvable.

We could very politely ask other countries, "Please, can we have some of your renewables? We don't want to build them in our back yard." This could also work on smaller political scales: you can imagine Massachusetts, which has the same population density as Britain, asking to borrow some of Arizona's desert.

Incidentally, there used to be an international trade in negative energy—about 100 years ago, Norway used to export *cold* to London in the form of ice.

There's one other thing: whatever plan we propose, demand and supply must add up *at all times*—during all weeks and all minutes throughout the year. Demand fluctuates. Electricity demand fluctuates on a daily cycle. Natural-gas demand for heating peaks in the winter and drops in the summer; in fact, in Britain it can more than double in midwinter. So we need a plan for storing energy in order to level out demand on all time scales.

You can level out hourly electrical demand by "pumped storage," which uses water in a mountaintop reservoir as a battery. You pump the water up to the reservoir, turning electrical energy into potential energy, and then later you let the water run back downhill through the turbines to generate electricity.

On a seasonal scale, you can pump solar-heated water into the ground in summer, and pump it back out in winter. There's a master-planned community called Drake Landing up in Alberta that has been doing this since 2007. They claim to have halved the usual natural-gas consumption for heating, which leads me to wonder why they didn't build everything to better insulation standards so that they wouldn't need any gas heat in the first place.

When I started reading my gas meter every week, my consumption plunged. To help me tinker with the thermostat, in 2004 I got a more sophisticated time-controlled model, and installed a thermostatic valve on every radiator in the house. I also replaced my boiler with a condensing boiler that extracts latent heat from the steam produced by setting fire to methane. I scored again in 2007 by having fluff insulation blown into the outside walls and attic and buying new double-glazed windows and doors.

JEVONS'S PARADOX

Coal was to Victorian technology as oil is to ours. As steam-powered machinery proliferated, coal consumption skyrocketed, and the question of how long Britian's reserves would last was hotly debated. In 1865, economist William Stanley Jevons published *The Coal Question*, in which he calculated that demand was doubling every 20 years—a clearly unsustainable rate—and predicted that "Rather more than a century of our present progress would exhaust our mines to the depth of 4,000 feet, or 1,500 feet deeper than our present deepest mine." (In fact, British coal production peaked in 1910.)

In the book, Jevons described the paradox now named for him: "It is wholly a confusion of ideas to suppose that the economical [i.e., efficient] use of fuel is equivalent to a diminished consumption. The very contrary is the truth. . . . It is the very economy of its use which leads to its extensive consumption . . . if the quantity of coal used in a blast-furnace, for instance, be diminished in comparison with the yield . . . the price of pig-iron will fall, but the demand for it [will] increase; and eventually the greater number of furnaces will more than make up for the diminished consumption of each."

At an average of 15 watts per square meter, harvesting concentrated solar power in the desert is our best option among the renewables. The yellow squares on this map are 600 kilometers on a side. Completely filling one of them with solar concentrators would supply power for a billion people at the European standard of consumption; doing the same for the world would require *two* such squares 1,000 kilometers on a side.

A PLAN THAT ADDS UP

So how do you we take a place like the U.K.—or Massachusetts, or New Jersey, or anywhere with a high population density—off fossil fuels? It would involve electrification of lots of transportation; flying less; riding your bike and taking the train more; insulating buildings better; getting people to read their meters; and electrifying building heating using heat pumps. And then you would meet the vastly increased demand for electricity from a mix of your own renewables; possibly nuclear power, which is a stopgap in the sense that uranium and thorium atoms are a finite resource on the scale of a millennium; possibly clean coal, which is also a stopgap, because coal is a finite resource on the scale of decades or centuries; and, finally, other people's renewables, which could be solar power in other people's deserts.

The wind farms needed to deliver 42 kilowatt-hours per day to the U.S. would cover 10 New Jerseys. Biofuels would take about 50 New Jerseys.

I'm emphatically *not* recommending any particular solution. My goal is to show you, to scale, all the options that are on the table, and the exchange rates among the different sources, so that there can be an informed discussion. If someone says, "I don't want solar power from someone else's desert, thank you," no problem—for each 60 square kilometers of solar power you cut, you need another one-gigawatt nuclear power station. Or if you say, "No no no, I don't like nuclear power," no problem—each nuclear power station can be replaced (on average) by 2,000 wind turbines, occupying an area of about 400 square kilometers. Then you just need to decide where you're going to put all those extra wind farms.

People often say, oh, a tiny square in the Sahara could satisfy all the world's energy consumption. Each yellow square in the map above would enable a European standard of living for everyone in Europe and North Africa—125 kilowatt-hours per day per person for one billion people. (The red square is for the population of Britain, or 60 million people. Fittingly, it's the size of Wales.) The yellow square is much smaller than the Sahara Desert, yes, but it is the size of Germany. So the message is, and always will be, that we're talking about a big building project. And if you want to mix in other renewables, fine, but the total area will only get bigger, because other renewables have *lower* power per unit area. If we put that same yellow square in North America, it would deliver your consumption—250 kilowatt-hours per day per person—for everyone in Canada, Mexico, and the U.S., and it would be half the size of Texas.

You don't want to just depend on arrays of solar panels, so let's sketch out some options. If the U.S. is serious about getting off fossil fuels by 2050, you could go for wind, nuclear, biomass, and solar-in-the-deserts in a big way.

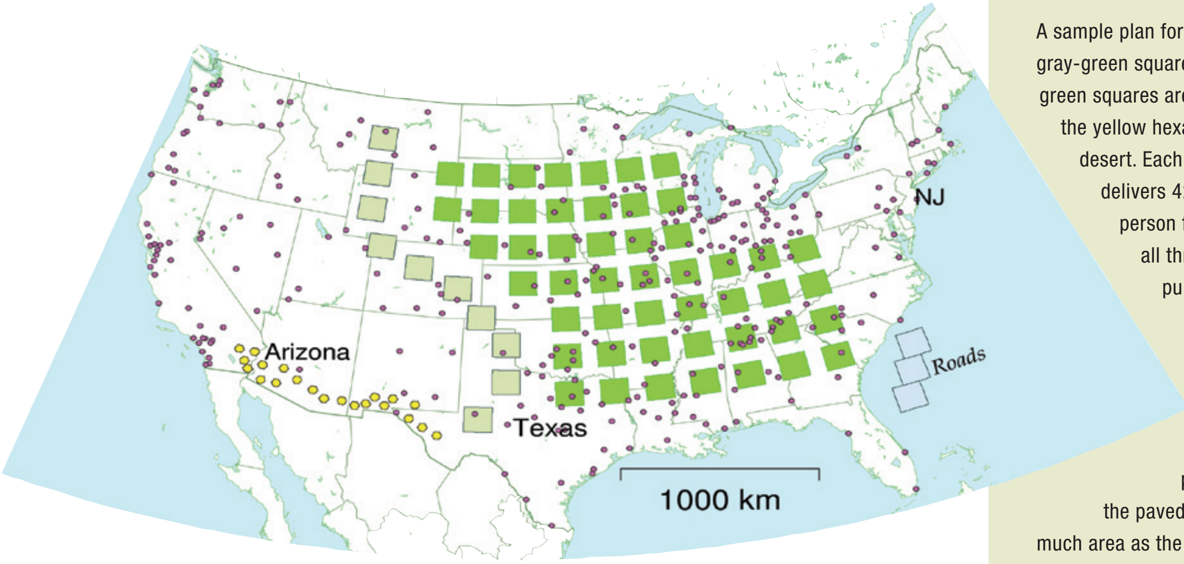
To show you the exchange rates, I'm going to map out 42 kilowatt-hours per day per person each of wind, of nuclear, of biomass, and of solar in deserts. That adds up to 168 lightbulbs per person, which, if some energy-saving measures are introduced, might maintain today's lifestyle. (Putting solar hot-water panels on your roofs would supply about half your residential hot-water needs in almost all climates, for example.)

As you can see from the map on the opposite page, the wind farms needed to deliver 42 kilowatt-hours per day per person would cover 10 New Jerseys, or about the area of California. The arrays in the desert to concentrate sunlight stations would be one-eighth of the size of Arizona. Energy crops are shown by the green squares in the Midwest—about 50 New Jerseys. And the nuclear plants, each about a kilometer square, would be a fivefold increase over today's levels.

Let me now personalize this. What does a community need to do? What does one person need to do? If 300 people say, "Let's get ourselves a wind turbine," and it's a standard two-megawatt turbine, that's 42 kilowatt-hours per day per person on average.

Los Angeles would be getting 42 kilowatt-hours per day per person from nuclear power if the city had—for itself—seven one-gigawatt power stations. Chicago would need five; Houston, four; Denver, Boston, Las Vegas, and Portland, Oregon, one each. Your biomass plantations, at 4,000 square meters per person, would be half of a football field devoted *to you* to deliver your 42 kilowatt-hours. And the solar-in-deserts would need 30 one-meter-square mirrors per person, focusing sunlight on a 1/400th share of a centralized collector tower.

What about the cost of building all these things? Money's important, but I give a physics-based talk because the laws of physics are timeless, whereas the "laws" of economics can change within 12 months. Nevertheless we can estimate the costs. At today's prices, British offshore wind farms cost twice as much, in terms of subsidies, as British onshore wind farms. Nuclear and clean coal's costs are unknown, because no one's built a nuclear power station in the last



A sample plan for the United States. The gray-green squares are wind farms, the bright green squares are bio-energy plantations, and the yellow hexagons are solar plants in the desert. Each of these three renewables delivers 42 kilowatt-hours per day per person for 300 million people, and all three are drawn to scale. The purple dots are your industry-standard one-gigawatt nuclear power plants (not drawn to scale) providing another 42 kilowatt-hours per day per person. For comparison, all the paved roads in the U.S. take up as much area as the three squares in the Atlantic. Each square is 20,000 square kilometers in size—the same area as New Jersey.

couple of decades, and clean coal is still at the pilot-plant stage. Hopefully they'll come in similar to onshore wind farms, but the error bars on costs are really quite large at the moment.

The total cost of doing something like this for Britain would come out to something like 14 billion pounds per year. Britain already spends 100 billion per year on energy, and another 100 billion on insurance. So 14 billion a year over the next 40 or so years compared with 200 billion a year sounds quite reasonable to me—you could view this as an energy and insurance policy all wrapped up in one. It's still a substantial number, and figuring out how to finance these things is going to be a challenge. But it's not unaffordable. It seems to me to be a solvable problem.

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

David MacKay (PhD '92) took his BA in natural sciences at Trinity College at the University of Cambridge, and came to Caltech on a Fulbright, founding the Caltech Environmental Task Force while earning his degree in computation and neural systems. He then returned to Cambridge, where he is now a professor of natural philosophy at the Cavendish Laboratory. He was elected a fellow of the Royal Society in 2009. As a physicist, his reseach focuses on information theory and machine learning.

As an environmentalist, MacKay says he was inspired by "reading* Caltech News *in the bath one evening when I came across an article by [Caltech physics professor David] Goodstein" warning that we could run out of cheap oil within the decade. But MacKay was also reading* The Skeptical Environmentalist, *by economics professor Bjorn Lomborg, who said that "everything is fine, there is plenty of energy. How could two intelligent people reach such different conclusions?" At the same time, MacKay was getting fed up with the "twaddle" in the form of incomprehensible, misleading, or downright wrong numbers being put out by the media, politicians, corporations trying to appear green, and environmentalists alike. This turned into a bunch of back-of-the-envelope calculations he posted on a website, which eventually turned into* Sustainable Energy — without the hot air, *an eminently readable, vastly entertaining, and remarkably thorough analysis of our energy options.

The book brought him a job offer from the U.K.'s Department of Energy and Climate Change, where he is now responsible for ensuring that scientific and engineering evidence underpin all the Department's work—the U.K. equivalent of former Caltech physics professor Steven Koonin (BS '72), who is now the Under Secretary for Science at the U.S. Department of Energy.

One of the U.K. Department's new projects is an engineering-based software tool to explore how demand-side and supply-side choices can be combined into energy pathways that maintain security of supply, and achieve Britain's target for greenhouse emissions reductions of at least 80 percent below 1990 levels.

This article was adapted by Douglas L. Smith from the presentation MacKay gave at Caltech on April 5, 2010. A video of the talk can be seen in the Caltech Streaming Theater. Go to http://today.caltech.edu/theater/list?subset=science.

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