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Meeting the world's energy needs entirely with wind, water, and solar power

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Abstract

The combustion of fossil fuels is largely responsible for the problems of climate change, air pollution, and energy insecurity. A combination of wind, water, and solar power is the best alternative to fossil fuels, the authors write, because renewable energy sources have near-zero emissions of greenhouse gases and other air pollutants, no long-term waste disposal problems, and no risks of catastrophic accidents. Compared with nuclear energy and biomass energy, the authors find that wind, water, and solar power, alone, would not only be advantageous but also feasible to meet 100 percent of the world's energy needs. They explain how renewable energy systems can be designed and operated to ensure that power generation reliably matches demand; they calculate that these energy sources would cost less than fossil fuels when all costs to society are considered; and they recommend policies for easing the transition to energy systems based entirely on wind, water, and solar power.

Keywords

bioenergy, climate change, fossil fuels, hydropower, nuclear power, solar power, wind power

In May 2013, the average daily level of carbon dioxide in the atmosphere passed 400 parts per million, an increase of more than 40 percent since the beginning of the industrial revolution and the highest level on Earth in several million years.[1] That same month, scientists reported that Arctic sea ice, one of the most visible and important indicators of global climate change, was melting faster than most climate models have predicted, raising the possibility that the summer Arctic will be nearly ice-free by as early as 2020 (Overland and Wang, 2013). Around the world, air pollution in mega-cities routinely exceeds international air quality standards set to protect human health. Globally, the use of oil for transportation grows unabated, exposing the world economy to price and supply volatility, and exacerbating political and environmental problems in countries where oil is produced and consumed.

These problems of climate change, air pollution, and energy insecurity are due primarily to the combustion of fossil fuels—mainly coal, oil, and natural gas.

Although increased energy efficiency, improved emissions-control technology, and oil sharing and stockpiling agreements can mitigate some of the negative environmental and energy-security impacts of fossil-fuel use, these measures ultimately do little more than alleviate the pressure of increases in population and affluence. In order to avoid serious environmental and economic damages from energy use, humans must stop using fossil fuels altogether, as soon as possible.

In the search for alternatives to fossil fuels, scientists and policy makers have focused their attention on three replacements that are widely believed to have lower emissions of greenhouse gases, the air pollutants responsible for climate change, than do fossil fuels: nuclear power; energy from biomass; and a combination of wind, water, and solar power. The third option—which includes wind turbines, photovoltaic power plants and rooftop systems, concentrated solar thermal power plants, small-scale hydroelectric plants, geothermal plants, tidal turbines, and wave energy converters—has several advantages over nuclear energy and bioenergy, including lower (near zero) emissions of greenhouse gases and air pollutants, no problems of long-term waste disposal, and no risks of catastrophic accidents. Despite the natural variability of wind, water, and solar power, they can deliver energy as reliably as, and more economically than, the current fossil-fuel-based system when all costs to society are considered. Indeed, energy systems worldwide can be run entirely on wind, water, and solar power, making it unnecessary to pursue the less desirable alternatives of nuclear power and bioenergy. But there are a number of steps that are needed to begin such a transition.

Why not bioenergy or nuclear power?

In order to ensure that an energy system has near-zero environmental impact even with long-term growth in population and economic activity, it must emit virtually no greenhouse gases or air pollutants over its entire lifecycle.[2] A truly sustainable system should be based on primary energy and material resources that are indefinitely renewable, recyclable, or replaceable with little or no impact on water quality, water use, and ecosystem integrity; pose no significant catastrophic risks; and present no major challenges with the disposal of long-term waste.

In 2009, Mark Jacobson, one of the authors of this article, evaluated several energy systems with respect to their impacts on global warming, air pollution, water supply, land use, wildlife, thermal pollution, water-chemical pollution, and nuclear weapons proliferation—and found that wind, water, and solar power have lower impacts in these categories than do nuclear or bioenergy power. He concluded that coal with carbon capture, corn ethanol, cellulosic ethanol, soy biodiesel, other biofuels, and nuclear power all are moderately or significantly worse than wind, water, and solar power at reducing greenhouse gas emissions and air pollution. Furthermore, nuclear and bioenergy systems can have significant problems in terms of land use, water use, resource availability, or catastrophic risk.[3] For example, even the most climate-friendly and least ecologically disruptive sources of bioethanol—such as native, perennial grasses (Tilman et al., 2006)—will cause air pollution mortality on the same order as gasoline—as many as 50,000 premature deaths per year in the United States—because burning ethanol creates smog that can cause serious respiratory problems (Anderson, 2009; Jacobson, 2007). Moreover, *any* use of land for the production of bioenergy feedstocks is worse for climate, water quality, soil, biodiversity, and overall ecosystem health than is the always-available option of restoring land to its ecologically best use and getting energy from other (non-biomass) sources. Put another way, getting energy from wind, water, or the sun rather than from bioenergy allows society to put land to better use than growing energy crops.

As for nuclear energy, there are many reasons that it is less desirable than wind, water, and solar power as a long-term global energy source. Perhaps most important is the security issue surrounding nuclear power—that is, the possibility of weapons-usable nuclear materials or radiological materials getting into the wrong hands. The growth of nuclear energy has increased the ability of nations and individuals to acquire or enrich uranium for nuclear weapons and obtain high-risk radioisotopes for radiological terrorism, and a large-scale worldwide increase in nuclear energy facilities could exacerbate this problem, putting the world at greater risk of a nuclear war or terrorist attack (Feiveson, 2009; Fissile Materials Working Group, 2011, 2012; Kessides, 2010; Macfarlane and Miller, 2007; Miller and Sagan, 2009; Ullom, 1994).

In terms of the environment, nuclear energy results in greater emissions of greenhouse gases than do alternative energy technologies, in part due to emissions from uranium refining and transport and reactor construction. Comprehensive reviews and analyses (Lenzen, 2008; Sovacool, 2008) find that nuclear power has life-cycle emissions of about 65 grams of carbon dioxide (or its equivalent) per kilowatt-hour of electricity generated: greater than the estimated 9 to 10 grams per kilowatt-hour emitted by wind power, 13 grams per kilowatt-hour emitted by solar thermal power, and 32 grams per kilowatt-hour emitted by photovoltaic systems (Sovacool, 2008). It also takes longer to site, permit, and construct a nuclear plant than, say, a wind farm—and in the meantime, electricity generation by conventional means continues to release greenhouse gases (Jacobson, 2009). Further, conventional nuclear fission relies on finite stores of uranium. Thus, a global-scale nuclear program with a once-through fuel cycle (in which spent nuclear fuel is treated as waste rather than re-used) could exhaust uranium supplies in roughly a century (Adamantiades and Kessides, 2009; Macfarlane and Miller, 2007).

Although the nuclear industry has improved the safety of reactors and has proposed safer—but generally untested—designs[4] (Adamantiades and Kessides, 2009; Mourogov et al., 2002; Penner et al., 2008; Piera, 2010; Rosner et al., 2011), the failures and mistakes of the past suggest that it is impossible to rule out the probability that even the most advanced reactors will be designed, built, or operated incorrectly. Even if the risks of catastrophe are very small, they are not zero (Feiveson, 2009), whereas with wind, small hydropower systems, and solar power, the dread-inducing risk of a large-scale catastrophe *is* zero. This is an important societal advantage.

Finally, conventional nuclear power produces radioactive waste, which must be stored for tens of thousands of years (Feiveson et al., 2011), raising issues of technical and institutional competence, cost, and intergenerational ethics (Adamantiades and Kessides, 2009; Barré, 1999; Macfarlane, 2011; von Hippel, 2008).

There are at least three alternatives to light water nuclear reactors, the nuclear fission reactors most in use today: breeder reactors, thorium reactors, and fusion reactors. The main advantages of breeder reactors are that they produce less low-level radioactive waste than do light water reactors and re-use the spent fuel, thereby extending uranium reserves, perhaps indefinitely (Penner et al., 2008; Purushotham et al., 2000; Till et al., 1997). In addition, some breeder technologies have technical features that make diversion and reprocessing difficult, albeit not impossible. However, breeder reactors have several disadvantages: They are too costly; they have special safety and reliability problems related to the use of sodium coolant; and they still pose serious nuclear proliferation risks (Cochran et al., 2010). For these reasons, Thomas B. Cochran, senior scientist at the Natural Resources Defense Council's Nuclear Program, and others (2010) argue that the development of breeder reactors should be abandoned.

Thorium as a nuclear fuel is more abundant than uranium, less likely to lead to nuclear weapons proliferation, and produces smaller amounts of long-lived radioactive waste (Macfarlane and Miller, 2007). Alternative energy, however, avoids these problems entirely. Moreover, nuclear engineers have relatively little experience with constructing or running thorium reactors.

Fusion of light atomic nuclei (for example, protium, deuterium, or tritium) theoretically could supply power indefinitely without long-lived radioactive wastes (Ongena and Van Oost, 2006; Tokimatsu et al., 2003). However, fusion still would produce short-lived waste that must be removed from the reactor core to avoid interference with operations, and in any case fusion is unlikely to be commercially available for at least another 50 years (Moyer, 2010; Tokimatsu et al., 2003), although some fusion experts believe it could be available by 2050 (*Bulletin of the Atomic Scientists*, 2013). By contrast, wind, solar, and small-scale hydropower are available today, can last indefinitely, and pose relatively little risk to wildlife[5] or humans.

Nonpartisan surveys in the United States mirror our assessment of wind and solar power versus nuclear. The 2007 MIT Energy Survey found that 76 percent of Americans favor increased use of solar and wind power, but only 35 percent favor increased use of nuclear power (Ansolabehere, 2007). More recent surveys by the Pew Research Center (2013) also show broad support for wind and solar energy but opposition to nuclear power. These findings appear relatively stable, in spite of efforts by the nuclear energy industry to persuade the public that nuclear power is a desirable energy option (Ramana, 2011). The public has a broader, more nuanced, and ultimately more rational view of the risks and benefits of nuclear power than does the nuclear industry, appropriately considering factors such as involuntary exposure to risk, the potential magnitude of accidents, inequities in risks and benefits, long-term implications of exposure, and the trustworthiness of the industry and the institutions overseeing it (Ramana, 2011). A comprehensive comparison of nuclear versus wind, water, and solar energy must take these factors into account.

The cost of wind, water, and solar energy

In a world powered entirely by wind, water, and sunshine, energy could be delivered as reliably as it is today, but at lower cost than in a business-as-usual world. The private[6] costs of generating onshore wind power, geothermal power, and hydropower already are less than the private costs of conventional fossil-fuel power (Delucchi and Jacobson, 2011). The cost of photovoltaic power is dropping rapidly, and if the photovoltaic industry continues to grow and improve technologically, by 2020 the cost will be comparable to the cost of conventional power, as will the cost of solar thermal power (Jacobson et al., 2013). We project that, within a decade, the private cost of all major wind, water, and solar-power technologies will be less than 9 cents per kilowatt-hour and less than the private cost of new fossil-fuel generation (Delucchi and Jacobson, 2011; Jacobson et al., 2013).[7]

For any energy option, the total cost to society is the private cost of generating power plus additional environmental or system-wide costs. For wind, water, and solar power, these additional costs include the costs of extra generation capacity, transmission, or storage needed to ensure that demand can be satisfied reliably. In an earlier study (Delucchi and Jacobson, 2011), we estimated that an expanded transmission system might cost about 1 cent per kilowatt-hour, and that the use of electric vehicle batteries as decentralized storage also might cost about 1 cent per kilowatt-hour, although there is considerable uncertainty in this latter estimate. Thus, within a decade, the total social cost of reliably delivered wind, water, and solar power is likely to be on the order of 11 cents per kilowatt-hour or less.

For conventional fossil-fuel power, the additional costs are the estimated value of the damages to human health, economic systems, and ecosystems from air pollution and climate change. Using findings in a comprehensive study by the National Research Council (2010), we estimated that in 2030 these damages would cost 2 cents to 15 cents per kilowatt-hour, with a midrange value of about 6 cents per kilowatt-hour (see Table 2 in Deluccchi and Jacobson, 2011). The total social cost of conventional fossil-fuel power—equal to these damage costs plus the private cost of at least 8 cents per kilowatt-hour—thus would be at least 10 cents per kilowatt-hour and could exceed 20 cents, whereas the total social cost of wind, water, and solar power would be 10 cents per kilowatt-hour or less.

Matching power supply to demand

In a 100 percent wind, water, and solar-energy world there are several methods of accommodating short-term variability in generation to ensure that supply reliably matches demand (Delucchi and Jacobson, 2011). One important method is to interconnect geographically dispersed, naturally variable energy sources to make a single large electrical grid in which individual facilities are far enough apart that it is unlikely that it will be windless or sunless *everywhere* on the grid. A related strategy is to combine complementary energy sources: for example, pairing wind power, which tends to peak at night, with solar power, which peaks in the middle of the day. Another important method is to use a controllable energy source, such as hydroelectric power, to fill temporary gaps between demand and wind or solar generation.

When generation exceeds demand, the excess power can be stored for later use. Storage can be at the generation site (for example, using excess energy to compress air in underground caverns), or at the points of end use (for example, by topping off electric vehicle batteries, or by producing hydrogen via electrolysis and storing it at hydrogen refueling stations). A complementary strategy is to oversize peak generation capacity to minimize the times when available wind or solar power is insufficient to meet demand, and to provide spare power to produce hydrogen for transportation, heating, and cooling.

It also is possible to manage demand. Smart demand-response management can shift flexible loads—such as some heating, cooling, and washing—to better match the availability of wind or solar power. And for all of these supply-and-demand management methods it is helpful to develop better weather forecasting, to better understand potential short-term changes in supply and demand.

Complementary and gap-filling energy resources, smart demand-response management, and better weather forecasting have little or no additional resource cost and hence should be employed as broadly as is technically and socially feasible. A wind, water, and solar power system will, however, require system-wide costs to interconnect resources over large geographic regions (resulting perhaps in a system known as a supergrid), employ some decentralized storage in vehicle batteries, and add excess capacity. The optimal system design and operation will vary spatially and temporally, but in general will have the lowest-cost combination of complementary and gap-filling generation technologies, long-distance interconnection, centralized and decentralized energy storage, hydrogen production, and generation overcapacity that reliably satisfies intelligently managed demand.

Recently, several studies have formally investigated the question of whether and how renewable energy systems can be designed and operated to ensure that power generation reliably matches demand. Engineer and computer programmer Ben Elliston and his colleagues (2012) at the University of New South Wales simulated a 100 percent renewable energy system—based on solar thermal, wind, photovoltaic, hydro, and biofuel gas-turbine power—that meets actual hourly demand in the Australian National Electricity Market in 2010. Energy engineer Ian G. Mason and his colleagues (2010) at the University of Canterbury performed a similar analysis for New Zealand, meeting demand mainly with hydropower, wind, and geothermal power. Physicist David Connolly and colleagues (2011) developed a model of the existing energy system in Ireland and created 100 percent renewable energy plans for the electricity, heating, and transportation sectors. Mathematical analyst Morten Grud Rasmussen and colleagues (2012) studied energy storage and supply-demand balancing in a fully renewable pan-European power system and found that a 100 percent renewable power system could meet demand using a combination of hydrogen storage, hydropower, and only a small amount of wind and solar overcapacity, with wind and solar providing more than 50 percent of the power. In the United States, the National Renewable Energy Laboratory's (2012) massive "Renewable Electricity Futures Study" concluded that commercially available renewable-energy technologies, combined with a more flexible electricity system, could comfortably supply 80 percent of US electricity in 2050, meeting hourly demand in every region of the country. Stanford graduate student Elaine K. Hart and Jacobson (2011), modeling the California electricity grid over two years, and Delaware Technical Community College energy instructor Cory Budischak and colleagues (2013), modeling the PJM Interconnection (a large regional grid in the eastern United States), find that at least 99 percent of delivered electricity can be produced carbon-free with wind, water, and solar resources.

Although much more research is needed to understand the optimal configuration of renewable energy systems in a wide range of conditions, the studies done so far indicate that there are not likely to be any technical or economic showstoppers anywhere in the world.

What is the best way to get to 100 percent?

The short answer is to expand and modify the transmission and distribution infrastructure to accommodate alternative energy systems and to increase production of battery-electric and hydrogen-fuel-cell vehicles, ships that run on hydrogen-fuel-cell-and-battery combinations, aircraft that fly on liquefied hydrogen, air- and ground-source heat pumps, electric resistance heating, and hydrogen for high-temperature processes in industrial operations. (In a 100 percent wind, water, and solar power world, hydrogen is produced for transportation and heating uses by electrolyzing water.)

A more detailed answer starts with the recognition that current energy markets, institutions, and policies have been developed to support the production and use of fossil fuels, not alternative energy. Because fossil-fuel energy systems have different production, transmission, and end-use costs and characteristics than do renewable energy systems, new policies are needed to ensure that wind, water and solar power develop as quickly and broadly as is socially desirable. These are some of the policies that can help facilitate and accelerate the transition:

Incentives for renewable electricity generation

State and national governments should develop, strengthen, or extend two existing incentives: Renewable Portfolio Standards, which require electricity suppliers to produce a certain fraction of their electricity from renewable energy sources; and Feed-In Tariffs, financial incentives that promote investment in renewable power generation infrastructure, typically by providing payments to owners of small-scale solar photovoltaic systems to cover the difference between renewable energy generation costs (including grid connection costs) and wholesale electricity prices. State and national governments also should create mechanisms for retiring coal-fired power plants as quickly as possible. Coal-burning plants are the single biggest source of air pollution in the United States, and many are old and inefficient.

Streamlined permitting and financing

State and local governments should streamline the permit approval process for wind, water, and solar-power generators and associated high-capacity transmission lines. They should establish and fund local programs to facilitate the installation of small-scale solar and wind power systems. These programs can include tax incentives, direct rebates, permit streamlining (for example, the creation of common codes, fee structures, and filing procedures across states and regions), "green" banks that provide public–private financing for distributed generation and energy efficiency projects, and the development of community-based renewable energy facilities, which allow people to invest in and benefit from renewable energy generation systems that are not located on their own property (as currently contemplated under a bill proposed in California).

Demand management

Government agencies should use municipal financing, incentives, and rebates to promote energy efficiency in buildings, appliances, and industrial processes. They should encourage utilities to use demand-response grid management to reduce the need for short-term energy backup on the grid. In conjunction with this, they should implement virtual net metering for small-scale energy systems and adopt time-of-use electricity rates to encourage charging at night.

Transportation policies

Governments should adopt legislation mandating the transition to plug-in electric vehicles for short- and medium-distance government transportation, and offer purchase incentives and rebates for commercial and personal vehicles. Governments should also develop comprehensive plans, guidelines, and incentives for the widespread installation of electric charging stations along public streets and in public and private commercial parking lots and garages, office and commercial buildings, civic centers, shopping centers, schools, and residential garages.

The coming energy transformation

The obstacles to powering the world with wind, water, and sunshine are primarily social and political, not technical or economic. If society continues to make decisions based on interest-group politics and chooses to support nuclear power, clean coal, and biofuels, energy use will continue to threaten the health and well-being of the ecosystems and inhabitants of the planet. But if society can muster the political will and implement sensible broad-based policies and social changes, it can solve the world's energy and environmental problems by mid-century.

Although this is a big undertaking, it does not need to happen overnight, and it is encouraging to recall that the world has undertaken large-scale infrastructure, industrial, and engineering projects before. During World War II, the United States and other countries rapidly transformed manufacturing facilities to produce hundreds of thousands of aircraft. In 1956, the United States began work on an interstate highway system that now extends for about 47,000 miles. The iconic Apollo program, widely considered one of the greatest engineering and technological accomplishments ever, put a man on the moon in less than a decade. These successes suggest that it is socially and politically possible to transform the global energy system and move toward a sustainable energy future.

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Notes

1. This milestone was the average daily level measured by instruments atop Mauna Loa in Hawaii, which is fairly representative of the Northern Hemisphere as a whole. Previously, the Mauna Loa station had recorded hourly spikes above 400 parts per million, and measuring stations in the Arctic had recorded average daily carbon dioxide levels above 400 parts per million. In May 2013, the global average was still just shy of 400 parts per million.
2. The material in this section is adapted from Jacobson and Delucchi (2011).
3. See Delucchi (2010) for a review of land-use, climate-change, and water-use impacts of biofuels.
4. For example, reactors with "passive safety" designs do not require operator actions or electronic feedback in order to shut the reactor down in certain types of emergencies, such as overheating due to loss of coolant.
5. For example, even though the media have highlighted the risks that wind turbines pose to birds, it turns out that wind projects kill far fewer birds than do fossil-fuel plants and fewer even than do nuclear power plants: 0.3 bird deaths per gigawatt-hour for wind power compared with 0.4 for nuclear power and 5.2 for fossil-fuel power (Sovacool, 2009).
6. The private cost is the monetary value of all labor and capital required to produce a good or service. In an ideal accounting, private costs do not include government subsidies or the estimated value of unpriced impacts, such as poor health due to air pollution, that result from production or consumption. (Loosely speaking, these unpriced impacts are "external" costs.)
7. The private cost of generating electricity is equal to the capital (or construction) cost, excluding subsidies, annualized over the life of the equipment, plus annual operating and maintenance costs, divided by the annual energy output (which is estimated by accounting for typical variability in wind and solar intensity). Projected costs assume evolutionary but not revolutionary improvements in technology.

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Mark Z. Jacobson is a professor of civil and environmental engineering and director of the Atmosphere/Energy Program at Stanford University. He is also a senior fellow at the Woods Institute for the Environment and the Precourt Institute for Energy, both at Stanford. The main goal of his research is to better understand severe atmospheric problems such as air pollution and global warming, and to develop and analyze large-scale renewable energy solutions to them. He has developed a number of computer models for simulating air pollution and its effects on climate. In 2009, Jacobson and Delucchi co-authored a seminal report on how to power the world on renewable energy alone.