Review of Solutions to Global Warming, Air Pollution, and Energy Security

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Abstract

This paper reviews and ranks major proposed energy-related solutions to global warming, air pollution mortality, and energy security while considering other impacts of the proposed solutions, such as on water supply, land use, wildlife, resource availability, thermal pollution, water chemical pollution, nuclear proliferation, and undernutrition. Nine electric power sources and two liquid fuel options are considered. The electricity sources include solar-photovoltaics (PV), concentrated solar power (CSP), wind, geothermal, hydroelectric, wave, tidal, nuclear, and coal with carbon capture and storage (CCS) technology. The liquid fuel options include corn-ethanol (E85) and cellulosic E85. To place the electric and liquid fuel sources on an equal footing, we examine their comparative abilities to address the problems mentioned by powering new-technology vehicles, including battery-electric vehicles (BEVs), hydrogen fuel cell vehicles (HFCVs), and flex-fuel vehicles run on E85. Twelve combinations of energy source-vehicle type are considered. Upon ranking and weighting each combination with respect to each of 11 impact categories, four clear divisions of ranking, or tiers, emerge. Tier 1 (highest-ranked) includes wind-BEVs and wind-HFCVs. Tier 2 includes CSP-BEVs, Geothermal-BEVs, PV-BEVs, tidal-BEVs, and wave-BEVs. Tier 3 includes hydro-BEVs, nuclear-BEVs, and CCS-BEVs. Tier 4 includes corn- and cellulosic-E85. Wind-BEVs ranked first in seven out of 11 categories, including the two most important, mortality and climate damage reduction. Although HFCVs are much less efficient than BEVs, wind-HFCVs are still very clean and were ranked second among all combinations. Tier 2 options provide significant benefits and are recommended. Tier 3 options are less desirable. However, hydroelectricity, which was ranked ahead of coal-CCS and nuclear with respect to climate and health, is an excellent load balancer, thus recommended. The Tier-4 combinations (cellulosic- and corn-E85) were ranked lowest overall and with respect to climate, air pollution, land use, wildlife damage, and chemical waste. Cellulosic-E85 ranked lower than corn-E85 overall, primarily due to its potentially larger land footprint based on new data and its higher upstream air pollution emissions than corn-E85. Whereas cellulosic-E85 may cause the greatest average human mortality, nuclear-BEVs cause the greatest upper-limit mortality risk due to the expansion of plutonium separation and uranium enrichment in nuclear energy facilities worldwide. Wind-BEVs and CSP-BEVs cause the least mortality. The footprint area of wind-BEVs is 2-6 orders of magnitude less than that of any other option. Because of their low footprint and pollution, wind-BEVs cause the least wildlife loss. The largest consumer of

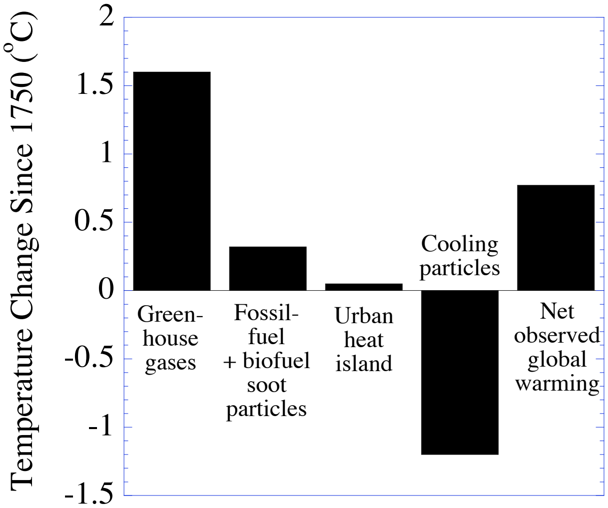
water is corn-E85. The smallest are wind-, tidal-, and wave-BEVs. The U.S. could theoretically replace all 2007 onroad vehicles with BEVs powered by 73,000-144,000 5-MW wind turbines, less than the 300,000 airplanes the U.S. produced during World War II, reducing U.S. CO_2 by 32.5-32.7% and nearly eliminating 15,000/yr vehicle-related air pollution deaths in 2020. In sum, use of wind, CSP, geothermal, tidal, PV, wave, and hydro to provide electricity for BEVs and HFCVs and, by extension, electricity for the residential, industrial, and commercial sectors, will result in the most benefit among the options considered. The combination of these technologies should be advanced as a solution to global warming, air pollution, and energy security. Coal-CCS and nuclear offer less benefit thus represent a opportunity cost loss, and the biofuel options provide no certain benefit and the greatest negative impacts.

1. Introduction

Air pollution and global warming are two of the greatest threats to human and animal health and political stability. Energy insecurity and rising prices of conventional energy sources are also major threats to economic and political stability. Many alternatives to conventional energy sources have been proposed, but analyses of such options have been limited in breadth and depth. The purpose of this paper is to review several major proposed solutions to these problems with respect to multiple externalities of each option. With such information, policy makers can make better decisions about supporting various options. Otherwise, market forces alone will drive decisions that may result in little benefit to climate, air pollution, or energy-security problems.

Indoor plus outdoor air pollution is the sixth-leading cause of death, causing over 2.4 million premature deaths worldwide[1]. Air pollution also increases asthma, respiratory illness, cardiovascular disease, cancer, hospitalizations, emergency-room visits, work-days lost, and school-days lost[2,3], all of which decrease economic output, divert resources, and weaken the security of nations.

Figure 1. Primary contributions to observed global warming from 1750 to today from global model calculations. The fossil-fuel plus biofuel soot estimate[4] accounts for the effects of soot on snow albedo. The remaining numbers were calculated by the author. Cooling aerosol particles include particles containing sulfate, nitrate, chloride, ammonium, potassium, certain organic carbon, and water, primarily. The sources of these particles differ, for the most part, than sources of fossil-fuel and biofuel soot.



Global warming enhances heat stress, disease, severity of tropical storms, ocean acidity, sea levels, and the melting of glaciers, snow pack, and sea ice[5]. Further, it shifts the location of viable agriculture, harms ecosystems and animal habitats, and changes the timing and magnitude of water supply. It is due to the globally-averaged difference between warming contributions by greenhouse gases, fossil-fuel plus biofuel soot particles, and the urban heat island effect, and cooling contributions by non-soot aerosol particles (Figure 1). The primary global warming pollutants are, in order, carbon dioxide gas, fossil-fuel plus biofuel soot particles, methane gas[4,6-10], halocarbons, tropospheric ozone, and nitrous oxide gas[5]. About half of actual global warming to date is being masked by cooling aerosol particles (Figure 1 and Ref. 5), thus, as such particles are removed by the clean up of air pollution, about half of hidden global warming will be unmasked. This factor alone indicates that addressing global warming quickly is critical. Stabilizing temperatures while accounting for anticipated future growth, in fact, requires about an 80% reduction in current emissions of greenhouse gases and soot particles.

Because air pollution and global warming problems are caused primarily by exhaust from solid, liquid, and gas combustion during energy production and use, such problems can be addressed only with large-scale changes to the energy sector. Such changes are also needed to secure an undisrupted energy supply for a growing population, particularly as fossil-fuels become more costsly and harder to find/extract.

This review evaluates and ranks 12 combinations of electric power and fuel sources from among 9 electric power sources, 2 liquid fuel sources, and 3 vehicle technologies, with respect to their ability to address climate, air pollution, and energy problems simultaneously. The review also evaluates the impacts of each on water supply, land use, wildlife, resource availability, thermal pollution, water chemical pollution, nuclear proliferation, and undernutrition.

Costs are not examined since policy decisions should be based on the ability of a technology to address a problem rather than costs (e.g., the U.S. Clean Air Act Amendments of 1970 prohibit the use of cost as a basis for determining regulations required to meet air pollution standards) and because costs of new technologies will change over time, particularly as they are used on a large scale. Similarly, costs of existing fossil fuels are generally increasing, making it difficult to estimate the competitiveness of new technologies in the short or long term. Thus, a major purpose of this paper is to provide quantitative information to policy makers about the most effective solutions to the problem discussed so that better decisions about providing incentives can be made.

The electric power sources considered here include solar photovoltaics (PV), concentrated solar power (CSP), wind turbines, geothermal power plants, hydroelectric power plants, wave devices, tidal turbines, nuclear power plants, and coal power plants fitted with carbon capture and storage (CCS) technology. The two liquid fuel options considered are corn-E85 (85% ethanol; 15% gasoline) and cellulosic-E85. To place the electric and liquid fuel sources on an equal footing, we examine their comparative abilities to address the problems mentioned by powering new-technology vehicles, including battery-electric vehicles (BEVs), hydrogen fuel cell vehicles (HFCVs), and E85-powered flex-fuel vehicles. We examine combinations of PV-BEVs, CSP-BEVs, wind-BEVs, wind-HFCVs, geothermal-BEVs, hydroelectric-BEVs, wave-BEVs, tidal-BEVs, nuclear-BEVs, CCS-BEVs, corn-E85 vehicles, and cellulosic-E85 vehicles. More combinations of electric power with HFCVs were not compared simply due to the additional effort required and since the options examined are the most commonly discussed. For the same reason, other fuel options, such as algae, butanol, biodiesel, sugar-cane ethanol, or hydrogen combustion; electricity options such as biomass; vehicle options such as hybrid vehicles, heating options such as solar hot water heaters; and geoengineering proposals, were not examined.

In the following sections, we describe the energy technologies, evaluate and rank each technology with respect to each of several categories, then provide an overall ranking of the technologies and summarize the results.

2. Description of Technologies

Below different proposed technologies for addressing climate change and air pollution problems are briefly discussed.

2a. Solar Photovoltaics (PVs)

Solar photovoltaics (PVs) are arrays of cells containing a material that converts solar radiation into direct current (DC) electricity[11]. Materials used today include amorphous silicon, polycrystalline silicon, micro-crystalline silicon, cadmium telluride, and copper indium selenide/sulfide. A material is doped to increase the number of positive (p-type) or negative (n-type) charge carriers. The resulting p- and n-type semiconductors are then joined to form a p-n junction that allows the generation of electricity when illuminated. PV performance decreases when the cell temperature exceeds a threshold of 45 ºC[12]. Photovoltaics can be mounted on roofs or combined into farms. Solar-PV farms today range from 10-60 MW although proposed farms are on the order of 150 MW.

2b. Concentrated Solar Power (CSP)

Concentrated Solar Power is a technology by which sunlight is focused (concentrated) by mirrors or reflective lenses to heat a fluid in a collector at high temperature. The heated fluid (e.g., pressurized steam, synthetic oil, molten salt) flows from the collector to a heat engine where a portion of the heat (up to 30%) is converted to electricity[13]. One type of collector is a set of parabolic-trough (long U-shaped) mirror reflectors that focus light onto a pipe containing oil that flows to a chamber to heat water for a steam generator that produces electricity. A second type is a central tower receiver with a field of mirrors surrounding it. The focused light heats molten nitrate salt that produce steam for a steam generator. By storing heat in a thermal storage media, such as pressurized steam, concrete, molten sodium nitrate, molten potassium nitrate, or purified graphite within an insulated reservoir before producing electricity, the parabolic-trough and central tower CSP plants can reduce the effects of solar intermittency by producing electricity at night. A third type of CSP technology is a parabolic dish-shaped (e.g., satellite dish) reflector that rotates to track the sun and reflects light onto a receiver, which transfers the energy to hydrogen in a closed loop. The expansion of hydrogen against a piston or turbine produces mechanical power used to run a generator or alternator to produce electricity. The power conversion unit is air cooled, so water cooling is not needed. Thermal storage is not coupled with parabolic-dish CSP.

2c. Wind

Wind turbines convert the kinetic energy of the wind into electricity. Generally, a gearbox turns the slow-turning turbine rotor into faster-rotating gears, which convert mechanical energy to electricity in a generator. Some late-technology turbines are gearless. The instantaneous power produced by a turbine is proportional to the third power of the instantaneous wind speed. However, because wind speed frequency distributions are Rayleigh in nature, the average power in the wind over a given period is linearly proportional to the mean wind speed of the Rayleigh distribution during that period[11]. The efficiency of wind power generation increases with the turbine height since wind speeds generally increase with increasing height. As such, larger turbines capture faster winds. Large turbines are generally sited in flat open areas of land, within mountain passes, on ridges, or offshore. Although less efficient, small turbines (e.g., 1-10 kW) are convenient for use in homes or city street canyons.

2d. Geothermal

Geothermal energy is energy extracted from hot water and steam below the Earth's surface. Steam or hot water from the Earth has been used historically to provide heat for buildings, industrial processes, and domestic water. Hot water and/or steam have also been used to generate electricity in geothermal power plants. Three major types of geothermal plants are dry steam, flash steam, and binary[13]. Dry and flash steam plants operate where geothermal reservoir temperatures are 180-370 ºC or higher. In both cases, two boreholes are drilled – one for steam alone (in the case of dry steam) or liquid water plus steam (in the case of flash steam) to flow up, and the second for condensed water to return after it passes through the plant. In the dry steam plant, the pressure of the steam rising up the first borehole powers a turbine, which drives a generator to produce electricity. About 70% of the steam recondenses after it passes through a condenser, and the rest is released to the air. Since CO_2, NO, SO_2, and H_2S in the reservoir steam do not recondense along with water vapor, these gases are emitted to the air. Theoretically, they could be captured, but they have not been to date. In a flash steam plant, the liquid water plus steam from the reservoir enters a flash tank held at low pressure, causing some of the water to vaporize ("flash"). The vapor then drives a turbine. About 70% of this vapor is recondensed. The remainder escapes with CO_2 and other gases. The liquid water is injected back to the ground. A binary system is used when the reservoir temperature is 120-180 ºC. Water rising up a borehole is kept in an enclosed pipe and heats a low-boiling-point organic fluid, such as isobutene or isopentane, through a heat exchanger. The evaporated organic turns a turbine that powers a generator, producing electricity. Because the water from the reservoir stays in an enclosed pipe when it passes through the power plant and is reinjected to the reservoir, binary systems produce virtually no emissions of CO_2, NO, SO_2, or H_2S. About 15% of geothermal plants today are binary plants.

2e. Hydroelectric

Hydroelectric power is currently the world's largest installed renewable source of electricity, supplying about 17.4% of total electricity in 2005[14]. Water generates electricity when it drops gravitationally, driving a turbine and generator. While most hydroelectricity is produced by water falling from dams, some is produced by water flowing down rivers (run-of-the-river electricity). Hydroelectricity is ideal for providing peaking power and smoothing intermittent wind and solar resources. When it is in spinning-reserve mode, it can provide electric power within 15-30 seconds. Hydroelectric power today is usually used for peaking power. The exception is when small reservoirs are in danger of overflowing, such as during heavy snowmelt during spring. In those cases, hydro is used for baseload.

2f. Wave

Winds passing over water create surface waves. The faster the wind speed, the longer the wind is sustained, the greater the distance the wind travels, and the greater the wave height. The power in a wave is generally proportional to the density of water, the square of the height of the wave, and the period of the wave[15]. Wave power devices capture energy from ocean surface waves to produce electricity. One type of device is a buoy that rises and falls with a wave, creating mechanical energy that is converted to electricity that is sent through an underwater transmission line to shore. Another type is a floating surface-following device, whose up-and-down motion increases the pressure on oil to drive a hydraulic ram to run a hydraulic motor.

2g. Tidal

Tides are characterized by oscillating currents in the ocean caused by the rise and fall of the ocean surface due to the gravitational attraction among the Earth, Moon, and Sun[13]. A tidal turbine is similar to a wind turbine in that it consists of a rotor that turns due to its interaction with water during the ebb and flow of a tide. A generator in a tidal turbine converts kinetic energy to electrical energy, which is transmitted to shore. The turbine is generally mounted on the sea floor and may or may not extend to the surface. The rotor, which lies under water, may be fully exposed to the water or placed within a narrowing duct that directs water toward it. Because of the high density of seawater, a slow-moving tide can produce significant tidal turbine power; however, water current speeds need to be at least 4 knots (2.05 m/s) for tidal energy to be economical. In comparison, wind speeds over land need to be about 7 m/s or faster for wind energy to be economical. Since tides run about six hours in one direction before switching directions for six hours, they are fairly predictable, so tidal turbines may potentially be used to supply baseload energy.

2h. Nuclear

Nuclear power plants today generally produce electricity after splitting heavy elements during fission. The products of the fission collide with water in a reactor, releasing energy, causing the water to boil, releasing steam whose enhanced partial pressure turns a turbine to generate electricity. The most common heavy elements split are ^{235}U and ^{239}Pu. When a slow-moving neutron hits ^{235}U, the neutron is absorbed, forming ^{236}U, which splits, for example, into ^{92}Kr, ^{141}Ba, three free neutrons, and gamma rays. When the fragments and the gamma rays collide with water in a reactor, they respectively convert kinetic energy and electromagnetic energy to heat, boiling the water. The element fragments decay further radioactively, emitting beta particles (high-speed electrons). Uranium is originally stored as small ceramic pellets within metal fuel rods. After 18-24 months of use as a fuel, the uranium's useful energy is consumed and the fuel rod becomes radioactive waste that needs to be stored for up to thousands of years. With breeder reactors, unused uranium and its product, plutonium, are extracted and reused, extending the lifetime of a given mass of uranium significantly.

2i. Coal-Carbon Capture and Storage

Carbon capture and storage (CCS) is the diversion of CO_2 from point emission sources to underground geological formations (e.g., saline aquifers, depleted oil and gas fields, unminable coal seams), the deep ocean, or as carbonate minerals. Geological formations worldwide may store up to 2000 Gt-CO_2[16], which compares with a fossil-fuel emission rate today of ~30 Gt-CO_2/yr. To date, CO_2 has been diverted underground following its separation from mined natural gas in several operations and from gasified coal in one case. However, no large power plant currently captures CO_2. Several options of combining fossil fuel combustion for electricity generation with CCS technologies have been considered. In one model[17], integrated gasification combined cycle (IGCC) technology would be used to gasify coal and produce hydrogen. Since hydrogen production from coal gasification is a chemical rather than combustion process, this method could result in relatively low emissions of classical air pollutants, but CO_2 emissions would still be large[18,19] unless it is piped to a geological formation. However, this model (with capture) is not currently feasible due to high costs. In a more standard model considered here, CCS equipment is added to an existing or new coal-fired power plant. CO_2 is then separated from other gases and injected underground after coal combustion. The remaining gases are emitted to the air. Other CCS methods include injection to the deep ocean and production of carbonate minerals. Ocean storage, however, results in ocean acidification. The dissolved CO_2 in the deep ocean would eventually equilibrate with that in the surface ocean, increasing the backpressure, expelling CO_2 to the air. Producing carbonate minerals has a long history. Joseph Black, in 1756, named carbon dioxide "fixed air" because it fixed to quicklime (CaO) to form $CaCO_3$. However, the natural process is slow and requires massive amounts of quicklime for large-scale CO_2 reduction. The process can be hastened by increasing temperature and pressure, but this requires additional energy.

2j. Corn and Cellulosic Ethanol

Biofuels are solid, liquid, or gaseous fuels derived from organic matter. Most biofuels are derived from dead plants or animal excrement. Biofuels, such as wood, grass, and dung, are used directly for home heating and cooking in developing countries and for electric power generation in others. Many countries also use biofuels for transportation. The most common transportation biofuels are various ethanol/gasoline blends and biodiesel. Ethanol is produced in a factory, generally from corn, sugarcane, wheat, sugar beet, or molasses. Microorganisms and enzyme ferment sugars or starches in these crops to produce ethanol. Fermentation of cellulose from switchgrass, wood waste, wheat, stalks, corn stalks, or miscanthus, can also produce ethanol, but the process is more difficult since natural enzyme breakdown of cellulose (e.g., as occurs in the digestive tracts of cattle) is slow. The faster breakdown of cellulose requires genetic engineering of enzymes. Here, we consider only corn and cellulosic ethanol and its use for producing E85 (a blend of 85% ethanol and 15% gasoline).

3. Available Resources

An important requirement for an alternative energy technology is that sufficient resource is available to power the technology and the resource can be accessed and used with minimal effort. In the cases of solar-PV, CSP, wind, tidal, wave, and hydroelectricity, the resources are the energy available from sunlight, sunlight, winds, tides, waves, and elevated water, respectively. In the case of nuclear, coal-CCS, corn ethanol, and cellulosic ethanol, it is the amount of uranium, coal, corn, and cellulosic material, respectively.

Table 1 gives estimated upper limits to the worldwide available energy (e.g., all the energy that can be extracted for electricity consumption, regardless of cost or location) and the technical potential energy (e.g., the energy that can feasibly be extracted in the near term considering cost and location) for each electric power source considered here. It also shows current installed power, average capacity factor, and current electricity generated for each source.

Table 1. Worldwide available energy, technical potential energy, current installed power, capacity factor of currently-installed power, and current electrical generation of the electric power sources considered here. For comparison, the 2005 world electric power production was 18.24 PWh/yr (2.08 TW, 1568 MTOE) and the energy production for all purposes was 133.0 PWh/yr (15.18 TW, 11,435 MTOE)[20]. Installed power and electricity generation are for 2005, except that wind and solar PV data are for 2007. 1 PW=10^{15} W.

Technology	Available Energy (PWh/yr)	Technical Potential Energy (PWh/yr)	Current Installed Power (GW)	Worldwide Capacity Factor of Technology in Place	Current Electricity Generation (TWh/yr)
Solar PV	14,900 (a)	<3,000 (a)	8.7 (b)	0.1-0.2 (c)	11.4 (d)
CSP	9250-11,800 (e)	1.05-7.8 (e)	0.354 (f)	0.13-0.25 (f)	0.4 (f)
Wind	630 (g)	410 (g)	94.1 (h)	0.205-0.42 (i)	173 (j)
Geothermal	1390 (k)	0.57-1.21 (l)	9 (m)	0.73 (n)	57.6 (m)
Hydroelectric	16.5 (m)	<16.5	778 (m)	0.416 (n)	2840 (m)
Wave	23.6 (k)	4.4 (k)	0.00075 (k)	0.21-0.25 (o)	0.0014 (j)
Tidal	7 (p)	0.18 (p)	0.26 (k)	0.2-0.35 (q)	0.565 (r)
Nuclear	4.1-122 for 90-300 y (s)	<4.1-122	371 (m)	0.808 (n)	2630 (m)
Coal-CCS	11 for 200 y (t)	<11	0	0.65-0.85 (u)	0

(a) Extractable power over land. Assumes the surface area over land outside of Antarctica is 135,000,000 km^2, 160 W solar panels with an area of 1.258 m^2 each, a globally-averaged capacity factor for photovoltaics of 15%, and a reduction of available photovoltaic area by one-third to allow for service and panels to be angled to prevent shading by each other. The technical potential is estimated as less than 20% of the total to account for low-insolation and exclusion areas.

(b) Data[21] for 2007. About 90% of the installed PV was tied to the grid.

(c) A PV capacity factor range of 0.1-0.2 is used based on running PVWatts[12] over many locations globally. The 3-year averaged capacity factor of 56 rooftop 160-W solar panels, each with an area of 1.258 m^2, at 37.3797 N, 122.1364 W was measured by the author as 0.158.

(d) Calculated from installed power and an assumed capacity factor of 15%.

(e) The available energy is calculated by dividing the land area from footnote (a) by the range of km^2/MW for CSP without storage given in the Appendix and multiplying the result by a mean CSP capacity factor of 19%. A technical potential for installed CSP is 630-4700 GW[16]. This was converted to PWh/yr assuming a capacity factor of 19%.

(f) The installed power and electricity generation are from Ref. 16. The low capacity factor is derived from these two . The high capacity factor is from Ref. 22. Neither includes storage.

(g) The number is the actual power wind turbines would generate, from Ref. 23. Assumes electric power is obtained from 1500 kW turbines with 77-m diameter rotors and hub heights of 80 m, spaced 6 turbines per square kilometer over the 12.7% of land worldwide outside of Antarctica where the wind speed exceeds 6.9 m/s. The average global wind speed over land at such locations is 8.4 m/s at 80 m hub height. The technical potential is estimated by assuming a 35% exclusion area beyond the 87% exclusion already accounted for by removing low-wind-speed areas over land worldwide (Table 2). A calculated exclusion area over the mid-Atlantic Bight is 31%[24].

(h) Data were for 2007[25].

(i) The low value is the current global average[14]. The high value is from the Appendix. The 2004-2007 average for wind turbines installed in the U.S. is 0.33-0.35[26].

(j) Calculated from installed power and low capacity factor.

(k) Refs. 13, 16.

(l) This range is the technical potential[27].

(m) Data were for 2005[14].

(n) Calculated from installed power and electricity generation.

(o) Calculated in Appendix.

(p) See text.

(q) Ref. 28.

(r) Data were for 2005[29].

(s) Low available energy is for once-through thermal reactors; high number is for light-water and fast-spectrum reactors, which have very low penetration currently. Low number of years is for known reserves. High number is for expected reserves[16].

(t) Coal reserves were 930 billion tons in 2006[30]. With 2400 kWh/ton and 60% (or 11 PWh/yr) of annual electricity produced by coal, coal could last 200 y if coal used did not increase.

(u) Refs. 31, 32.

3a. Solar-PV

Globally, about 1700 TW (14,900 PWh/yr) of solar power are theoretically available over land for PVs, before removing exclusion zones of competing land use or high latitudes, where solar insolation is low. The capture of even 1% of this power would supply more than the world's power needs. Cumulative installed solar photovoltaic power at the end of 2007 was 8.7 GW (Table 1), with less than 1 GW in the form of PV power stations and most of the rest on rooftops. The capacity factor of solar PV ranges from 0.1 to 0.2, depending on location, cloudiness, panel tilt, and efficiency of the panel. Current-technology PV capacity factors rarely exceed 0.2, regardless of location worldwide, based on calculations that account for many factors, including solar cell temperature, conversion losses, and solar insolation[12].

3b. CSP

The total available energy worldwide for CSP is about one-third less than that for solar-PV since the land area required per installed MW of CSP without storage is about one-third greater than that of installed PV. With thermal storage, the land area for CSP increases since more solar collectors are needed to provide energy for storage, but so does total energy output, resulting in a similar total available energy worldwide for CSP with or without storage. Most CSP plants installed to date have been in California, but many projects are now being planned worldwide. The capacity factor of a solar-thermal power plant typically without storage ranges from 13-25% (Table 1 and references therein).

3d. Wind

The globally-available wind power over land in locations worldwide with mean wind speeds exceeding 6.9 m/s at 80 m is about 72 TW (630-700 PWh/yr), as determined from data analysis[23]. This resource is five times the world's total power production and 20 times the world's electric power production (Table 1). Earlier estimates of world wind resources were not based on a combination of sounding and surface data for the world or performed at the height of at least 80 m. The wind power available over the U.S. is about 55 PWh/yr, almost twice the current U.S. energy consumption from all sources and more than 10 times the electricity consumption[23]. At the end of 2007, 94.1 GW of wind power was installed worldwide, producing just over 1% of the world's electric power (Table 1). The countries with the most installed wind capacity were Germany (22.2 GW), the United States (16.8 GW), and Spain (15.1 GW), respectively[25]. Denmark generates about 19% of its electric power from wind energy. The average capacity factor of wind turbines installed in the U.S. between 2004-2007 was 33-35%, which compares with 22% for projects installed before 1998[26]. Of the 58 projects installed from 2004-2006, 25.9% had capacity factors greater than 40%.

For land-based wind energy costs without subsidy to be similar to those of a new coal-fired power plant, the annual-average wind speed at 80 meters must be at least 6.9 meters per second (15.4 miles per hour)[33]. Based on the mapping analysis[23], 15% of the data stations (thus, statistically, land area) in the United States (and 17% of land plus coastal offshore data stations) have wind speeds above this threshold (globally, 13 % of stations are above the threshold) (Table 2). Whereas, the mean wind speed over land globally from the study was 4.54 m/s, that at locations with wind speeds exceeding 6.9 m/s (e.g., those locations in Table 2) was 8.4 m/s. Similarly, the mean wind speed over all ocean stations worldwide was 8.6 m/s, but that over ocean stations with wind speeds exceeding 6.9 m/s was 9.34 m/s.

Table 2. Percent of sounding and surface station locations with mean annual wind speeds at 80 m > 6.9 m/s[23]. These percentages can be used as a rough surrogate for the percent of land area in the same wind speed regime due to the large number of stations (>8000) used.

Region	% Stations > 6.9 m/s
Europe	14.2
North America	19
United States over land	15
United States over land and near shore	17
South America	9.7
Oceania	21.2
Africa	4.6
Asia	2.7
Antarctica	60
Global over land	13

Although offshore wind energy is more expensive than onshore wind energy, it has been deployed significantly in Europe. A recent analysis indicated that wind resources off the shallow Atlantic coast could supply a significant portion of U.S. electric power on its own[24]. Water depths along the west coast of the U.S. become deeper faster than along the east coast, but another recent analysis indicates significant wind resources in several areas of shallow water offshore of the west coast as well[34].

3e. Geothermal

The Earth has a very large reservoir of geothermal energy below the surface; however, most of it is too deep to extract. Although 1390 PWh/yr could be reached[16], the technical potential is about 0.57-1.21 PWh/yr due to cost limitations[27].

3f. Hydroelectric

About 5% or more of potential hydroelectric power worldwide has been tapped. The largest producers of hydroelectricity worldwide are China, Canada, Brazil, U.S., Russia, and Norway, respectively· Norway uses hydro for nearly all (98.9%) of its electricity generation. Brazil and Venezuela use hydro for 83.7% and 73.9%, respectively, of their electricity generation[20].

3g. Wave

Wave potential can be estimated by considering that 2% of the world's 800,000 km of coastline exceeds 30 kW/m in wave power density. Thus, about 480 GW (4.2 PWh/yr) of power output can ultimately be captured[16].

3h. Tidal

The globally-averaged dissipation of energy over time due to tidal fluctuations may be 3.7 TW[35]. The energy available in tidal fluctuations of the oceans has been estimated as 0.6 EJ[36]. Since this energy is dissipated in four semi-diurnal tidal periods at the rate of 3.7 TW, the tidal power available for energy generation without interfering significantly with the tides may be about 20% of the dissipation rate, or 0.8 TW. A more practical exploitable limit is 0.02 TW[13].

3i. Nuclear

As of April 1, 2008, 439 nuclear power plants were installed in 31 countries (including 104 in the U.S., 59 in France, 55 in Japan, 31 in the Russian Federation, and 20 in the Republic of Korea). The U.S. produces more electric power from nuclear energy than any other country (29.2% of the world total in 2005)[20]. France, Japan, and Germany follow. France uses nuclear power to supply 79% of its electricity. At current nuclear electricity production rates, there are enough uranium reserves (4.7-14.8 MT[16]) to provide nuclear power in current "once-through" fuel cycle reactors for about 90-300 years (Table 1). With breeder reactors, which allow spent uranium to be reprocessed for additional fuel, the reprocessing also increases the ability of uranium and plutonium to be weaponized more readily than in once-through reactors.

4. Effects on Climate-Relevant Emissions

In this section, the CO_2-equivalent (CO_2e) emissions (emissions of CO_2 plus those of other greenhouse gases multiplied by their global warming potentials) of each energy technology are reviewed. We also examine CO_2e emissions of each technology due to planning and construction delays relative to those from the technology with the least delays ("opportunity-cost emissions"), leakage from geological formations of CO_2 sequestered by coal-CCS, and the emissions from the burning of cities resulting from nuclear weapons explosions potentially resulting from nuclear-energy expansion.

4a. Lifecycle Emissions

Table 3 summarizes ranges of the lifecycle CO_2e emission per kWh of electricity generated for the electric power sources considered (all technologies except the biofuels).

For some technologies (wind, solar PV, CSP, tidal, wave, hydroelectric), climate-relevant lifecycle emissions occur only during the construction, installation, maintenance, and decommissioning of the technology. For geothermal, emissions also occur due to evaporation of dissolved CO_2 from hot water in flash- or dry-steam plants, but not in binary plants. For corn ethanol, cellulosic ethanol, coal-CCS, and nuclear, additional emissions occur during the mining and production of the fuel. For biofuels and coal-CCS, emissions also occur as an exhaust component during combustion.

Table 3. Equivalent carbon-dioxide lifecycle, opportunity-cost emissions due to planning-to-operation delays relative to the technology with the least delay, and war/terrorism/leakage emissions for each electric power source considered (g-CO_2e/kWh). All numbers are referenced or derived in the Appendix.

Technology	Lifecycle	Opportunity cost emissions due to delays	War / terrorism (nuclear) or 500-year leakage (CCS)	Total
Solar PV	19-59	0	0	19-59
CSP	8.5-11.3	0	0	8.5-11.3
Wind	2.8-7.4	0	0	2.8-7.4
Geothermal	15.1-55	1-6	0	16.1-61
Hydroelectric	17-22	31-49	0	48-71
Wave	21.7	20-41	0	41.7-62.7
Tidal	14	20-41	0	34-55
Nuclear	9-70	59-106	0-4.1	68-180.1
Coal-CCS	255-442	51-87	1.8-42	307.8-571

4a.i. Wind

Wind has the lowest lifecycle CO_2e among the technologies considered. For the analysis, we assume that the mean annual wind speed at hub height of future turbines ranges from 7-8.5 m/s. Wind speeds 7 m/s or higher are needed for the direct cost of wind to be competitive over land with that of other new electric power sources[33]. About 13% of land outside of Antarctica has such wind speeds at 80 m (Table 2), and the average wind speed over land at 80 m worldwide in locations where the mean wind speed is 7 m/s or higher is 8.4 m/s[23]. The capacity factor of a 5 MW turbine with a 126 m diameter rotor in 7-8.5 m/s wind speeds is 0.294-0.425 (Appendix), which encompasses the measured capacity factors, 0.33-0.35, of all wind farms installed in the U.S. between 2004-2007[26]. As such, this wind speed range is the relevant range for considering the large-scale deployment of wind. The energy required to manufacture, install, operate, and scrap a 600 kW wind turbine has been calculated to be $\sim 4.3 \times 10^6$ kWh per installed MW[37]. For a 5 MW turbine operating over a lifetime of 30 years under the wind-speed conditions given, and assuming carbon emissions based on that of the average U.S. electrical grid, the resulting emissions from the turbine are 2.8-7.4 g-CO_2e/kWh and the energy payback time is 1.6 months (at 8.5 m/s) to 4.3 months (at 7 m/s). Even under a 20-year lifetime, the emissions are 4.2-11.1 g-CO_2e/kWh, lower than those of all other energy sources considered here. Given that many turbines from the 1970s still operate today, a 30-year lifetime is more realistic.

4a.ii. CSP

CSP is estimated as the second-lowest emitter of CO_2e. For CSP, we assume an energy payback time of 5-6.7 months[38-39] and a CSP plant lifetime of 40 years[39], resulting in an emission rate of 8.5-11.3 g-CO_2e/kWh (Appendix).

4a.iii. Wave and Tidal

Few analyses of the lifecycle carbon emissions for wave or tidal power have been performed. For tidal power, we use 14 g-CO_2e/kWh[40], determined from a 100 MW tidal turbine farm with an energy payback time of 3-5 months. Emissions for a 2.5 MW farm were 119 g-CO_2e/kWh[40], but because for large-scale deployment, we consider only the larger farm. For wave power, we use 21.7 g-CO_2e/kWh[41], which results in an energy payback time of 1 year for devices with an estimated lifetime of 15 years.

4a.iv. Hydroelectric

By far the largest component of the lifecycle emissions for a hydroelectric power plant is the emission during construction of the dam. Since such plants can last 50-100 years or more, their lifecycle emissions are relatively low, around 17-22 g-CO_2e/kWh[40,31]. In addition, some CO_2 and CH_4 emissions from dams can occur due to microbial decay of dead organic matter under the water of a dam, particularly if the reservoir was not logged before being filled[42]. Such emissions are generally highest in tropical areas and lowest in northern latitudes.

4a.v. Geothermal

Geothermal power plant lifecycle emissions include those due to constructing the plant itself and to evaporation of carbonic acid dissolved in hot water drawn from the Earth's crust. The latter emissions are almost eliminated in binary plants. Geothermal plant lifecycle emissions are estimated as 15 g-CO_2e/kWh[43] whereas the evaporative emissions are estimated as 0.1 g-CO_2e/kWh for binary plants and 40 g-CO_2e/kWh for non-binary plants[27].

4a.vi. Solar-PV

For solar PV, the energy payback time is generally longer than that of other renewable energy systems, but depends on solar insolation. Old PV systems generally had a payback time of 1-5 years[41,44,45]. New systems consisting of CdTe, silicon ribbon, multicrystalline silicon, and monocrystaline silicon under Southern European insolation conditions (1700 kWh/m^2/yr), have a payback time over a 30-year PV module life of 1-1.25, 1.7, 2.2, and 2.7 years, respectively, resulting in emissions of 19-25, 30, 37, and 45 g- CO_2e/kWh, respectively[46]. With insolation of 1300 kWh/m^2/yr (e.g., Southern Germany), the emissions range is 27-59 g-CO_2e/kWh. Thus, the overall range of payback time and emissions may be estimated as 1-3.5 years and 19-59 g- CO_2e/kWh, respectively. These payback times are generally consistent with those of other studies[47,48]. Since large-scale PV deployment at very high latitudes is unlikely, such latitudes are not considered for this payback analysis.

4a.vii. Nuclear

Nuclear power plant emissions include those due to uranium mining, enrichment, and transport and waste disposal as well as those due to construction, operation, and decommissioning of the reactors. We estimate the lifecycle emissions of new nuclear power plants as 9-70 g-CO_2e/kWh, with the lower number from an industry estimate[49] and the upper number slightly above the average of 66 g-CO_2e/kWh[50] from a review of 103 new and old lifecycle studies of nuclear energy. Three additional studies[51,48,16] estimate mean lifecycle emissions of nuclear reactors as 59, 16-55, and 40 g-CO_2e/kWh, respectively; thus, the range appears within reason.

4a.viii. Coal-CCS

Coal-CCS power plant lifecycle emissions include emissions due to the construction, operation, and decommissioning of the coal power plant and CCS equipment, the mining and transport of the coal, and carbon dioxide release during CCS. The lifecycle emissions of a coal power plant, excluding direct emissions but including coal mining, transport, and plant construction/decommissioning, range from 175-290 g-CO_2e/kWh[49]. Without

CCS, the direct emissions from coal-fired power plants worldwide are around 790-1020 g-CO_2e/kWh. The CO_2 direct emission reduction efficiency due to CCS is 85-90%[32]. This results in a net lifecycle plus direct emission rate for coal-CCS of about 255-440 g-CO_2e/kWh, the highest rate among the electricity-generating technologies considered here. The low number is the same as that calculated for a supercritical pulverized-coal plant with CCS[52].

The addition of CCS equipment to a coal power plant results in an additional 14-25% energy requirement for coal-based integrated gasification combined cycle (IGCC) systems and 24-40% for supercritical pulverized coal plants with current technology[32]. Most of the additional energy is needed to compress and purify CO_2. This additional energy either increases the coal required for an individual plant or increases the number of plants required to generate a fixed amount of electricity for general consumption. Here, we define the kWh generated by the coal-CCS plant to include the kWh required for the CCS equipment plus that required for outside consumption. As such, the g-CO_2e/kWh emitted by a given coal-CCS plant does not change relative to a coal plant without CCS, due to adding CCS; however, either the number of plants required increases or the kWh required per plant increases.

4a.ix. Corn and Cellulosic Ethanol

Several studies have examined the lifecycle emissions of corn and cellulosic ethanol[53-61] . These studies generally accounted for the emissions due to planting, cultivating, fertilizing, watering, harvesting, and transporting crops, the emissions due to producing ethanol in a factory and transporting it, and emissions due to running vehicles, although with differing assumptions in most cases. Only one of these studies[58] accounted for the emissions of soot, the second-leading component of global warming (Introduction), cooling aerosol particles, nitric oxide gas, carbon monoxide gas, or detailed treatment of the nitrogen cycle. That study[58] was also the only one to account for the accumulation of CO_2 in the atmosphere due to the time lag between biofuel use and regrowth[62]. Only three studies[58,60,61] considered substantially the change in carbon storage due to (a) converting natural land or crop land to fuel crops, (b) using a food crop for fuel, thereby driving up the price of food, which is relatively inelastic, encouraging the conversion of land worldwide to grow more of the crop, and (c) converting land from, for example, soy to corn in one country, thereby driving up the price of soy and encouraging its expansion in another country.

The study that performed the land use calculation in the most detail[61], determined the effect of price changes on land use change with spatially-distributed global data for land conversion between noncropland and cropland and an econometric model. It found that converting from gasoline to ethanol (E85) vehicles could increase lifecycle CO_2e by over 90% when the ethanol is produced from corn and around 50% when it is produced from switchgrass. Delucchi[58], who treated the effect of price and land use changes more approximately, calculated the lifecycle effect of converting from gasoline to corn and switchgrass E90. He estimated that E90 from corn ethanol might reduce CO_2e by about 2.4% relative to gasoline. In China and India, such a conversion might increase equivalent carbon emissions by 17% and 11%, respectively. He also estimated that ethanol from switchgrass might reduce U.S. CO_2e by about 52.5% compared with light-duty gasoline in the U.S. We use results from these two studies to bound the lifecycle emissions of E85. These results will be applied shortly to compare the CO_2e changes among electric power and fuel technologies when applied to vehicles in the U.S.

4b. Carbon Emissions Due to Opportunity Cost From Planning-to-Operation Delays

The investment in an energy technology with a long time between planning and operation increases carbon dioxide and air pollutant emissions relative to a technology with a short time between planning and operation. This occurs because the delay permits the longer operation of higher-carbon emitting existing power generation, such as natural gas peaker plants or coal-fired power plants, until their replacement occurs. In other words, the delay results in an opportunity cost in terms of climate- and air-pollution-relevant emissions. In the future, the power mix will likely become cleaner; thus, the "opportunity-cost emissions" will probably decrease over the long term. Ideally, we would model such changes over time. However, given that fossil-power construction continues to increase worldwide simultaneously with expansion of cleaner energy sources and the uncertainty of the rate of change, we estimate such emissions based on the current power mix.

The time between planning and operation of a technology includes the time to site, finance, permit, insure, construct, license, and connect the technology to the utility grid.

The time between planning and operation of a nuclear power plant includes the time to obtain a site and construction permit, the time between construction permit approval and issue, and the construction time of the plant. In March, 2007, the U.S. Nuclear Regulatory Commission approved the first request for a site permit in 30 years. This process took 3.5 years. The time to review and approve a construction permit is another 2 years and the time between the construction permit approval and issue is about 0.5 years. Thus, the minimum time for preconstruction approvals (and financing) is 6 years. We estimate the maximum time as 10 years. The time to construct a nuclear reactor depends significantly on regulatory requirements and costs. Because of inflation in the 1970s and more stringent safety regulation on nuclear power plants placed shortly before and after the Three-Mile Island accident in 1979, U.S. nuclear plant construction times increased from around 7 years in 1971 to 12 years in 1980[63]. The median construction time for reactors in the U.S. built since 1970 is 9 years[64]. U.S. regulations have been streamlined somewhat, and nuclear power plant developers suggest that construction costs are now lower and construction times shorter than they have been historically. However, projected costs for new nuclear reactors have historically been underestimated[64] and construction costs of all new energy facilities have recently risen. Nevertheless, based on the most optimistic future projections of nuclear power construction times of 4-5 years[65] and those times based on historic data[64], we assume future construction times due to nuclear power plants as 4-9 years. Thus, the overall time between planning and operation of a nuclear power plant ranges from 10-19 years.

The time between planning and operation of a wind farm includes a development and construction period. The development period, which includes the time required to identify a site, purchase or lease the land, monitor winds, install transmission, negotiate a power-purchase agreement, and obtain permits, can take from 0.5-5 years, with more typical times from 1-3 years. The construction period for a small to medium wind farm (15 MW or less) is 1 year and for a large farm is 1-2 years[66]. Thus, the overall time between planning and operation of a large wind farm is 2-5 years.

For geothermal power, the development time can, in extreme cases, take over a decade but with an average time of 2 years[27]. We use a range of 1-3 years. Construction times for a cluster of geothermal plants of 250 MW or more are at least 2 years[67]. We use a range of 2-3 years. Thus, the total planning-to-operation time for a large geothermal power plant is 3-6 years.

For CSP, the construction time is similar to that of a wind farm. For example, Nevada Solar One required about 1.5 years for construction. Similarly, an ethanol refinery requires about 1.5 years to construct. We assume a range in both cases of 1-2 years. We also assume the development time is the same as that for a wind farm, 1-3 years. Thus, the overall planning-to-operation time for a CSP plant or ethanol refinery is 2-5 years. We assume the same time range for tidal, wave, and solar-PV power plants.

The time to plan and construct a coal-fired power plant without CCS equipment is generally 5-8 years. CCS technology would be added during this period. The development time is another 1-3 years. Thus, the total planning-to-operation time for a standard coal plant with CCS is estimated to be 6-11 years. If the coal-CCS plant is an IGCC plant, the time may be longer since none has been built to date.

Dams with hydroelectric power plants have varying construction times. Aswan Dam required 13 years (1889-1902). Hoover Dam required 4 years (1931 to 1935). Shasta Dam required 7 years (1938-1945). Glen Canyon Dam required 10 years (1956 to 1966). Gardiner Dam required 8 years (1959-1967). Construction on Three Gorges Dam in China began on December 14, 1994 and is expected to be fully operation only in 2011, after 15 years. Plans for the dam were submitted in the 1980s. Here, we assume a normal range of construction periods of 6-12 years and a development period of 2-4 years for a total planning-to-operation period of 8-16 years.

We assume that after the first lifetime of any plant, the plant is refurbished or retrofitted, requiring a downtime of 2-4 years for nuclear, 2-3 years for coal-CCS, and 1-2 years for all other technologies. We then calculate the CO_2e emissions per kWh due to the total downtime for each technology over 100 years of operation assuming emissions during downtime will be the average current emission of the power sector. Finally, we subtract such emissions for each technology from that of the technology with the least emissions to obtain the "opportunity-cost" CO_2e emissions for the technology. The opportunity-cost emissions of the least-emitting technology is, by definition, zero. Solar-PV, CSP, and wind all had the lowest CO_2e emissions due to planning-to-operation time, so any could be used to determine the opportunity cost of the other technologies.

We perform this analysis for only the electricity-generating technologies. For corn and cellulosic ethanol the CO_2e emissions are already equal to or greater than those of gasoline, so the downtime of an ethanol refinery is unlikely to increase CO_2e emissions relative to current transportation emissions.

Results of this analysis are summarized in Table 3. For solar-PV, CSP, and wind, the opportunity cost was zero since these all had the lowest CO_2e emissions due to delays. Wave and tidal had an opportunity cost only because the lifetimes of these technologies are shorter than those of the other technologies due to the harsh conditions of being on the surface or under ocean water, so replacing wave and tidal devices will occur more frequently than replacing the other devices, increasing down time of the former. Although hydroelectric power plants have very long lifetimes, the time between their planning and initial operation is substantial, causing high opportunity cost CO_2e emissions for them. The same problem arises with nuclear and coal-CCS plants. For nuclear, the opportunity CO_2e is much larger than the lifecycle CO_2e. Coal-CCS's opportunity-cost CO_2e is much smaller than its lifecycle CO_2e. In sum, the technologies that have moderate to long lifetimes and that can be planned and installed quickly are those with the lowest opportunity cost CO_2e emissions.

4c. Effects of Leakage on Coal-CCS Emissions

Carbon capture and sequestration options that rely on the burial of CO_2 underground run the risk of CO_2 escape from leakage through existing fractured rock/overly porous soil or through new fractures in rock or soil resulting from an earthquake. Here, a range in potential emissions due to CO_2 leakage from the ground is estimated.

The ability of a geological formation to sequester CO_2 for decades to centuries varies with location and tectonic activity. IPCC[32] summarizes CO_2 leakage rates for an enhanced oil recovery operation of 0.00076% per year, or 1% over 1000 years and CH_4 leakage from historical natural gas storage systems of 0.1-10% per 1000 years. Thus, while some well-selected sites could theoretically sequester 99% of CO_2 for 1000 years, there is no certainty of this since tectonic activity or natural leakage over 1000 years is not possible to predict. Because liquefied CO_2 injected underground will be under high pressure, it will take advantage of any horizontal or vertical fractures in rocks, to try to escape as a gas to the surface. Because CO_2 is an acid, its low pH will also cause it to weather rock over time. If a leak from an underground formation occurs, it is not clear whether it will be detected or, if it is detected, how the leak will be sealed, particularly if it is occurring over a large area.

Here, we estimate CO_2 emissions due to leakage for different residence times of carbon dioxide stored in a geological formation. The stored mass (S, e.g., Tg) of CO_2 at any given time t in a reservoir resulting from injection at rate I (e.g., Tg/yr) and e-folding lifetime against leakage τ is

$$S(t)= S(0)e^{-t/\tau}+\tau I(1-e^{-t/\tau}) \tag{1}$$

The average leakage rate over t years is then

$$L(t)= I- S(t)/t \tag{2}$$

If 99% of CO_2 is sequestered in a geological formation for 1000 years (e.g., IPCC[32], , p. 216), the e-folding lifetime against leakage is approximately τ =100,000 years. We use this as our high estimate of lifetime and τ=5000 years as the low estimate, which corresponds to 18% leakage over 1000 years, closer to that of some observed methane leakage rates. With this lifetime range, an injection rate corresponding to an 80-95% reduction in CO_2 emissions from a coal-fired power plant with CCS equipment[32], and no initial CO_2 in the geological formation, the CO_2 emissions from leakage averaged over 100 years from Equations 1 and 2 is 0.36-8.6 g-CO_2/kWh; that averaged over 500 years is 1.8-42 g-CO_2/kWh, and that averaged over 1000 years is 3.5-81 g-CO_2/kWh. Thus, the longer the averaging period, the greater the average emissions over the period due to CO_2 leakage. We use the average leakage rate over 500 years as a relevant time period for considering leakage.

4d. Effects of Nuclear Energy on Nuclear War and Terrorism Damage

Because the production of nuclear weapons material is occurring only in countries that have developed civilian nuclear energy programs, the risk of a limited nuclear exchange between countries or the detonation of a nuclear device by terrorists has increased due to the dissemination of nuclear energy facilities worldwide. As such, it is a valid exercise to estimate the potential number of immediate deaths and carbon emissions due to the burning of buildings and infrastructure associated with the proliferation of nuclear energy facilities and the resulting proliferation of nuclear weapons. The number of deaths and carbon emissions, though, must be multiplied by a probability range of an exchange or explosion occurring to estimate the overall risk of nuclear energy proliferation. Although concern at the time of an explosion will be the deaths and not carbon emissions, policy makers today must weigh all the potential future risks of mortality and carbon emissions when comparing energy sources.

Here, we detail the link between nuclear energy and nuclear weapons and estimate the emissions of nuclear explosions attributable to nuclear energy. The primary limitation to building a nuclear weapon is the availability of purified fissionable fuel (highly-enriched uranium or plutonium)[68]. Worldwide, nine countries have known nuclear weapons stockpiles (U.S., Russia, U.K., France, China, India, Pakistan, Israel, North Korea). In addition, Iran is pursuing uranium enrichment, and 32 other countries have sufficient fissionable material to produce weapons. Among the 42 countries with fissionable material, 22 have facilities as part of their civilian nuclear energy program, either to produce highly-enriched uranium or to separate plutonium, and facilities in 13 countries are active[68]. Thus, the ability of states to produce nuclear weapons today follows directly from their ability to produce nuclear power. In fact, producing material for a weapon requires merely operating a civilian nuclear power plant together with a sophisticated plutonium separation facility. The Treaty of Non-Proliferation of Nuclear Weapons has been signed by 190 countries. However, international treaties safeguard only about 1% of the world's highly-enriched uranium and 35% of the world's plutonium[68]. Currently, about 30,000 nuclear warheads exist worldwide, with 95% in the U.S. and Russia, but enough refined and unrefined material to produce another 100,000 weapons[69].

The explosion of fifty 15-kt nuclear devices (a total of 1.5 MT, or 0.1% of the yields proposed for a full-scale nuclear war) during a limited nuclear exchange in megacities could burn 63-313 Tg of fuel, adding 1-5 Tg of soot to the atmosphere, much of it to the stratosphere, and killing 2.6-16.7 million people[68]. The soot emissions would cause significant short- and medium-term regional cooling[70]. Despite short-term cooling, the CO_2 emissions would cause long-term warming, as they do with biomass burning[62]. The CO_2 emissions from such a conflict are estimated here from the fuel burn rate and the carbon content of fuels. Materials have the following carbon contents: plastics, 38-92%; tires and other rubbers, 59-91%; synthetic fibers, 63-86%[71]; woody biomass, 41-45%; charcoal, 71%[72]; asphalt, 80%; steel, 0.05-2%. We approximate roughly the carbon content of all combustible material in a city as 40-60%. Applying these percentages to the fuel burn gives CO_2 emissions during an exchange as 92-690 Tg-CO_2. The annual electricity production due to nuclear energy in 2005 was 2768 TWh/yr. If one nuclear exchange as described above occurs over the next 30 years, the net carbon emissions due to nuclear weapons proliferation caused by the expansion of nuclear energy worldwide would be 1.1-4.1 g-CO_2/kWh, where the energy generation assumed is the annual 2005 generation for nuclear power multiplied by the number of years being considered. This emission rate depends on the probability of a nuclear exchange over a given period and the strengths of nuclear devices used. Here, we bound the probability of the event occurring over 30 years as between 0 and 1 to give the range of possible emissions for one such event as 0 to 4.1 g-CO_2/kWh. This emission rate is placed in context in Table 3.

4e. Analysis of CO_2e due to converting vehicles to BEVs, HFCVs, or E85 vehicles.

Here, we estimate the comparative changes in CO_2e emissions due to each of the 11 technologies considered when they are used to power all (small and large) onroad vehicles in the U.S. if such vehicles were converted to BEVs, HFCVs, or E85 vehicles. In the case of BEVs, we consider electricity production by all nine electric power sources. In the case of HFCVs, we assume the hydrogen is produced by electrolysis, with the electricity derived from wind power. Other methods of producing hydrogen are not analyzed here for convenience. However, estimates for another electric power source producing hydrogen for HFCVs can be estimated by multiplying a calculated parameter for the same power source producing electricity for BEVs by the ratio of the wind-HFCV to wind-BEV parameter (found in the Appendix). HFCVs are less efficient than BEVs, requiring a little less than three times the electricity for the same motive power, but

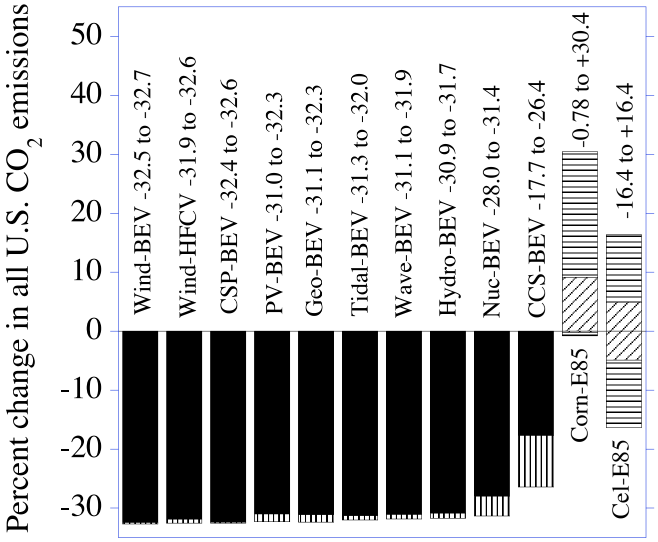
HFCVs are still more efficient than pure internal combustion (ESI) and have the advantage that the fueling time is shorter than the charging time for electric vehicle (generally 1-30 hours, depending on voltage, current, energy capacity of battery). A BEV-HFCV hybrid may be an ideal compromise but is not considered here.

In 2007, 24.55% of CO_2 emissions in the U.S. were due to direct exhaust from onroad vehicles. An additional 8.18% of total CO_2 was due to the upstream production and transport of fuel (Appendix). Thus, 32.73% is the largest possible reduction in U.S. CO_2 (not CO_2e) emissions due to any vehicle-powering technology. The upstream CO_2 emissions are about 94.3% of the upstream CO_2e emissions[58].

Figure 2 compares calculated percent changes in total emitted U.S. CO_2 emissions due to each energy-vehicle combination considered here. It is assumed that all CO_2e increases or decreases due to the technology have been converted to CO_2 for purposes of comparing with U.S. CO_2 emissions. Due to land use constraints, it is unlikely that corn or cellulosic ethanol could power more than 30% of U.S. onroad vehicles, so the figure also shows CO_2 changes due to 30% penetrations of E85. The other technologies, aside from hydroelectric power (limited by land as well), could theoretically power the entire U.S. onroad vehicle fleet so are not subject to the 30% limit.

Converting to corn-E85 could cause either no change in or increase CO_2 emissions by up to 9.1% with 30% E85 penetration (Appendix, I37). Converting to cellulosic-E85 could change CO_2 emissions by +4.9 to -4.9% relative to gasoline with 30% penetration (Appendix, J16). Running 100% of vehicles on electricity provided by wind, on the other hand, could reduce U.S. carbon by 32.5-32.7% since wind turbines are 99.2-99.8% carbon free over a 30-year lifetime and the maximum reduction possible from the vehicle sector is 32.73%. Using HFCVs, where the hydrogen is produced by wind electrolysis, could reduce U.S. CO_2 by about 31.9-32.6%, slightly less than using wind-BEVs since more energy is required to manufacture the additional turbines needed for wind-HFCVs. Running BEVs on electricity provided by solar-PV can reduce carbon by 31-32.3%. Nuclear-BEVs could reduce U.S. carbon by 28.0-31.4%. Of the electric power sources, coal-CCS producing vehicles results in the least emission reduction due to the lifecycle, leakage, and opportunity-cost emissions of coal-CCS.

Figure 2. Percent changes in U.S. CO_2 emissions upon replacing 100% of onroad (light- and heavy-duty) vehicles with different energy technologies and assuming all CO_2e has been converted to CO_2. Numbers are derived in the Appendix and account for all factors identified in Table 3. For all cases, low and high estimates are given. In all cases except the E85 cases, solid represents the low estimate and solid+vertical lines, the high. For corn and cellulosic E85, low and high values for 30% (slanted lines) instead of 100% (slanted+horizontal lines) penetration are also shown.



5. Effects on Air Pollution Emissions and Mortality

Although climate change is a significant driver for clean energy systems, the largest impact of energy systems worldwide today is on human mortality, as indoor plus outdoor air pollution kills over 2.4 million people annually (Introduction), with most of the air pollution due to energy generation or use.

Here, we examine the effects of the energy technologies considered on air pollution-relevant emissions and their resulting mortality. For wind, solar-PV, CSP, tidal, wave, and hydroelectric power, air-pollution relevant emissions arise only due to the construction, installation, maintenance, and decommissioning of the technology and as a result of planning-to-operation delays (Section 4b). For corn and cellulosic ethanol, emissions are also due to production of the fuel and ethanol-vehicle combustion. For non-binary geothermal plants (about 85% of existing plants) emissions also arise due to evaporation of NO, SO_2, and H_2S. The level of direct emissions is about 5% of that of a coal-fired power plant. For binary geothermal plants, such emissions are about 0.1% those of a coal-fired power plant. For nuclear power, pollutant emissions also include emissions due to the mining, transport, and processing of uranium. It is also necessary to take into the account the potential fatalities due to nuclear war or terrorism caused by the proliferation of nuclear energy facilities worldwide.

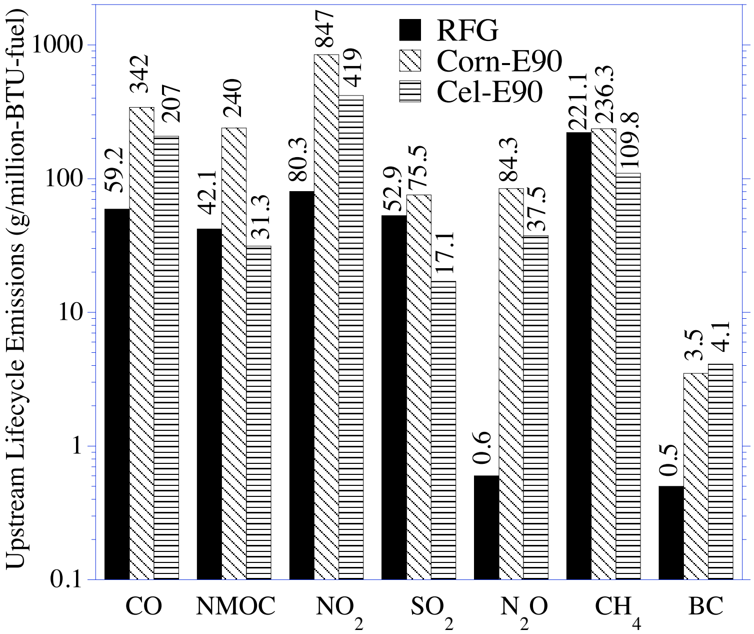
For coal-CCS, emissions also arise due to coal combustion since the CCS equipment itself generally does not reduce pollutants aside from CO_2. For example, with CCS equipment, the CO_2 is first separated from other gases after combustion. The remaining gases, such as SO_x, NO_x, NH_3, and Hg are discharged to the air. Because of the higher energy requirement for CCS, more non-CO_2 pollutants are generally emitted to the air compared with the case of no capture when a plant's fuel use is increased to generate a fixed amount of electric power for external consumption. For example, in one case, the addition of CCS equipment for operation of an IGCC plant was estimated to increase fuel use by 15.7%, SO_x emissions by 17.9%, and NO_x emissions by 11%[32]. In another case, CCS equipment in a pulverized coal plant increased fuel use by 31.3%, increased NO_x emissions by 31%, and increased NH_3 emissions by 2200% but the addition of another control device decreased SO_x emissions by 99.7%[32].

In order to evaluate the technologies, we estimate the change in the U.S. premature death rate due to onroad vehicle air pollution in 2020 after converting current onroad light- and heavy-duty gasoline vehicles to either BEVs, HFCVs, or E85 vehicles. Since HFCVs eliminate all tailpipe air pollution when applied to the U.S. vehicle fleet[19,18] as do BEVs, the deaths due to these vehicles are due only to the lifecycle emissions of the vehicles themselves and of the power plants producing electricity for them or for H_2 electrolysis. We assume lifecycle emissions of the vehicles themselves are similar for all vehicles so do not evaluate those emissions. We estimate deaths due to each electricity-generating technology as one minus the percent reduction in total CO_2e emissions due to the technology (Table 3) multiplied by the total number of exhaust- plus upstream-emission deaths (gas and particle) attributable to 2020 light- and heavy-duty gasoline onroad vehicles, estimated as ~15,000 in the U.S. from 3-D model calculations similar to those performed previously[73]. Thus, the deaths due to all BEV and HFCV options are attributed only to the electricity generation plant itself (as no net air pollution emanates from these vehicles). Because the number of deaths with most options is relatively small, the error arising from attributing CO_2e proportionally to other air pollutant emissions may not be so significant. Further, since CO_2e itself enhances mortality through the effect of its temperature and water vapor changes on air pollution[73], using it as a surrogate may be reasonable.

For nuclear energy, we add, in the high case, the potential death rate due to a nuclear exchange, as described in Section 4d, which could kill up to 16.7 million people. Dividing this number by 30 years and the ratio of the U.S. to world population today (302 million / 6.602 billion) gives an upper limit to deaths scaled to U.S. population of 25,500/year attributable to nuclear energy. We do not add deaths to the low estimate, since we assume the low probability of a nuclear exchange is zero.

The 2020 premature death rates due to corn- and cellulosic-E85 are calculated by considering 2020 death rate due to exhaust, evaporative, and upstream emissions from light- and heavy-duty gasoline onroad vehicles, the changes in such death rates between gasoline and E85**.** Changes in deaths due to the upstream emissions from E85 production were determined as follows. Figure 3 shows the upstream lifecycle emissions for multiple gases and black carbon from reformulated gasoline (RFG), corn-E90, and cellulosic-E90[58]. The upstream cycle accounts for fuel dispensing, fuel distribution and storage, fuel production, feedstock transmission, feedstock recovery, land-use changes, cultivation, fertilizer manufacture, gas leaks and flares, and emissions displaced. The figure indicates that the upstream cycle emissions of CO, NO_2, N_2O, and BC may be higher for both corn- and cellulosic E90 than for RFG. Emissions of NMOC, SO_2, and CH_4 are also higher for corn-E90 than for RFG but lower for cellulosic-E90 than for RFG. Weighting the emission changes by the low health costs per unit mass of pollutant from Spadaro and Rabl[74] gives a rough estimate of the health-weighed upstream emission changes of E90 versus RFG. The low health cost, which applies to rural areas, is used since most upstream emissions changes are away from cities. The result is an increase in the corn-E90 death rate by 20% and the cellulosic-E90 death rate by 30% (due primarily to the increase in BC of cellulosic-E90 relative to corn-E90), compared with RFG. Multiplying this result by 25%, the estimated ratio of upstream emissions to upstream plus exhaust emissions (Section 4e) gives death rate increases of 5.0% and 7.5% for corn- and cellulosic-E90, respectively, relative to RFG. The changes in onroad deaths between gasoline and E85 were taken from the only study to date that has examined this issue with a 3-D computer model over the U.S.[75] The study found that a complete penetration of E85-fueled vehicles (whether from cellulose or corn) might increase the air pollution premature death rate in the U.S. by anywhere from zero to 185 deaths/yr in 2020 over gasoline vehicles. The emission changes in that study were subsequently supported[76].

Figure 3. Upstream lifecycle emissions of several individual pollutants from corn-E90 and cellulosic-E90 relative to reformulated gasoline (RFG)[58].



An additional effect of corn- and cellulosic ethanol on mortality is through its effect on undernutrition. The competition between crops for food and fuel has reduced the quantity of food produced and increased food prices. Other factors, such as higher fuel costs, have also contributed to food price increases. Higher prices of food, in particular, increase the risk of starvation in many parts of the world. WHO[1] estimates that 6.2 million people died in 2000 from undernutrition, primarily in developing countries. Undernutrition categories include being underweight, iron deficiency, vitamin-A deficiency, and zinc deficiency. As such, death due to undernutrition does not require starvation. When food prices increase, many people eat less and, without necessarily starving, subject themselves to a higher chance of dying due to undernutrition and resulting susceptibility to disease. Here, we do not quantify the effects of corn-E85 or cellulosic-E85 on mortality due to the lack of a numerical estimate of the relationship between food prices and undernutrition mortality but note that it is probably occurring.

Figure 4 indicates that E85 may increase premature deaths compared with gasoline, due primarily to upstream changes in emissions but also due to changes in onroad vehicle emissions. Cellulosic ethanol may increase overall deaths more than corn ethanol, although this result rests heavily on the precise particulate matter upstream emissions of corn- versus cellulosic-E85. Due to the uncertainty of upstream and onroad emission death changes, it can be concluded that E85 is unlikely to improve air quality compared with gasoline and may worsen it.

Figure 4. Estimates of future (c. 2020) U.S. premature deaths per year from vehicles replacing light- and heavy-duty gasoline onroad vehicles and their upstream emissions assuming full penetration of each vehicle type or fuel, as discussed in the text. Low (solid) and high (solid+vertical lines) estimates are given. In the case of nuc-BEV, the upper limit of the number of deaths, scaled to U.S. population, due to a nuclear exchange caused by the proliferation of nuclear energy facilities worldwide is also given (horizontal lines). In the case of corn-E85 and cellulosic E85, the dots are the additional U.S. death rate due to upstream

emissions from producing and distributing E85 minus those from producing and distributing gasoline (see text) and the slanted lines are the additional tailpipe emissions of E85 over gasoline for the U.S.[75].

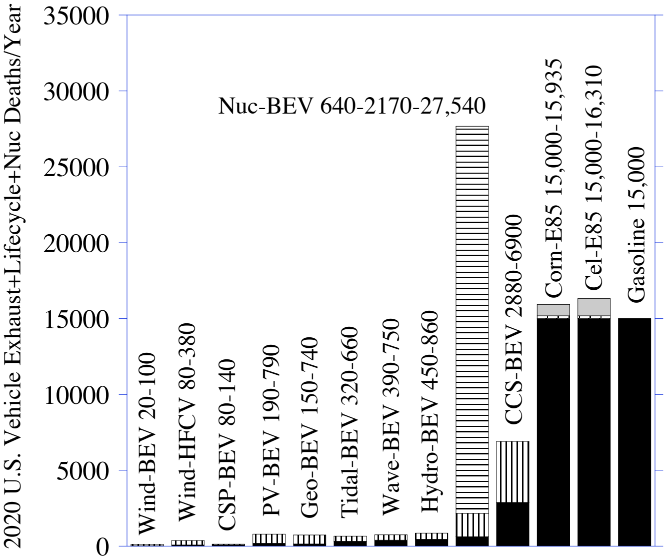


Figure 4 also indicates that each E85 vehicle should cause more air-pollution related death than each vehicle powered by any other technology considered, except to the extent that the risk of a nuclear exchange due to the spread of plutonium separation and uranium enrichment in nuclear energy facilities worldwide is considered. This conclusion holds regardless of the penetration of E85. For example, with 30% penetration, corn-E85 may kill 4500-5000 people/year more than CSP-BEVs at the same penetration. Because corn- and cellulosic-E85 already increase mortality more than any other technology considered, the omission of undernutrition mortality due to E85 does not affect the conclusions of this study. Emissions due to CCS-BEVs are estimated to kill more people prematurely than any other electric power source powering vehicles if nuclear explosions are not considered. Nuclear electricity causes the second-highest death rate among electric power sources with respect to lifecycle and opportunity-cost emissions. The least damaging technologies are wind-BEV followed by CSP-BEV and wind-HFCV.

6. Land and Ocean Use

In this section, the land, ocean surface, or ocean floor required by the different technologies is considered. Two categories of land use are evaluated: the footprint on the ground, ocean surface, or ocean floor and the spacing around the footprint. The footprint is more relevant since it is the actual land, water surface, or sea floor surface removed from use for other purposes and the actual wildlife habitat area removed or converted (in the case of hydroelectricity) by the energy technology. The spacing area is relevant to the extent that it is the physical space over which the technology is spread thus affects people's views (in the case of land or ocean surface) and the ability of the technology to be implemented due to competing uses of property. For wind, wave, tidal, and nuclear power, the footprint and spacing differ; for the other technologies, they are effectively the same.

In the case of wind, wave, and tidal power, spacing is needed between turbines or devices to reduce the effect of turbulence and energy dissipation caused by one turbine or device on the performance of another. One equation for the spacing area (A, m^2) needed by a wind turbine to minimize interference by other turbines in an array is A=4D x 7D, where D is the rotor diameter (m)[11]. This equation predicts that for a 5-MW turbine with a 126 m diameter rotor, an area of 0.44 km^2 is needed for array spacing. Over land, the area between turbines may be natural habitat, open space, farmland, ranch land, or used for solar energy devices, thus it is not wasted. On ridges, where turbines are not in a 2-D array but are lined up adjacent to each other, the spacing between the tips of turbine rotors may be one diameter, and the space required is much smaller since the array is one- instead of two-dimensional. Over water, wind turbines are also frequently closer to each other in the direction perpendicular to the prevailing wind to reduce local transmission line lengths.

6.1. Wind

The footprint on the ground or ocean floor/surface of one large (e.g., 5 MW) wind turbine (with a tubular tower diameter, including a small space around the tube for foundation, of 4-5 m) is about 13-20 m^2. Temporary dirt access roads are often needed to install a turbine. However, these roads are generally not maintained, so vegetation grows over them, as indicated in photographs of numerous wind farms. When, as in most cases, wind farms are located in areas of low vegetation, vehicle access for maintenance of the turbines usually does not require maintained roads. In some cases, turbines are located in more heavily vegetated or mountainous regions where road maintenance is more critical. However, the large-scale deployment of wind will require arrays of turbines primarily in open areas over land and ocean. In such cases, the footprint of wind energy on land is effectively the tower area touching the ground. Wind farms, like all electric power sources, also require a footprint due to transmission lines. Transmission lines within a wind farm are always underground. Those between the wind farm and a nearby public utility electricity distribution system are usually underground, but long distance transmission usually is not. In many cases, a public utility transmission pathway already exists near the wind farm and the transmission capacity needs to be increased. In other cases, a new transmission path is needed. We assume such additional transmission pathways apply roughly equally to all most electric power sources although this assumption may result in a small error in footprint size.

6.2. Wave

For surface wave power, the space between devices is open water that cannot be used for shipping because of the proximity of the devices to one another. The footprint on the ocean surface of one selected 750 kW device is 525 m^2 (Appendix), larger than that of a 5 MW wind turbine. However, the spacing between wave devices (about 0.025 km^2, Appendix) is less than that needed for a wind turbine.

6.3. Tidal

Many tidal turbines are designed to be completely underwater (e.g., resting on the ocean floor and not rising very high) although some designs have a component protruding above water. Since ocean-floor-based turbines do not interfere with shipping, the ocean area they use is not so critical as that used by other devices. However, some concerns have been raised about how sea life might be affected by tidal turbines. The footprint area of one sample ocean-floor-based 1 MW tidal turbine is about 288 m^2 (Appendix) larger than the footprint area of a larger, 5 MW wind turbine. The array spacing of tidal turbines must be a similar function of rotor diameter as that of a wind turbine since tidal turbines dissipate tidal energy just as wind turbines dissipate wind energy. However, because tidal turbine rotor diameters are smaller than wind turbine rotors for generating similar power (due to the higher density of water than air), the spacing between tidal turbines is lower than that between wind turbines if the equation $A= 4D \times 7D$ is used for tidal turbines.

6.4. Nuclear

In the case of nuclear power, a buffer zone around each plant is needed for safety. In the U.S., nuclear power plant areas are divided into an owner-controlled buffer region, an area restricted to some plant employees and monitored visitors, and a vital area with further restrictions. The owner-controlled buffer regions are generally left as open space to minimize security risks. The land required for nuclear power also includes that for uranium mining and disposal of nuclear waste. Estimates of the lands required for uranium mining and nuclear facility with a buffer zone are 0.06 ha-yr/GWh and 0.26 ha-yr/GWh, respectively, and that for waste for a single sample facility is about 0.08 km^2 [31] For the average plant worldwide, this translates into a total land requirement per nuclear facility plus mining and storage of about 20.5 km^2. The footprint on the ground (e.g., excluding the buffer zone only) is about 4.9-7.9 km^2.

6.5. Solar-PV and CSP

The physical footprint and spacing of solar-PV and CSP are similar to each other. The area required for a 160 W PV panel and walking space is about 1.9 m^2 (Appendix), or 1.2 km^2 per 100 MW installed, whereas that required for a 100 MW CSP plant without storage is 1.9-2.4 km^2 (Appendix). That with storage is 3.8-4.7 km^2 (Appendix footnote S42). The additional area when storage is used is for additional solar collectors rather than for the thermal storage medium (which require little land). The additional collectors transfer solar energy to the storage medium for use in a turbine at a later time (e.g., at night), thereby increasing the capacity factor of the turbine. The increased capacity factor comes at the expense of more land and collectors and the need for storage equipment. Currently, about 90% of installed PV is on rooftops. However, many PV power plants are expected in the future. Here, we estimate that about 30% of solar-PV will be on rooftops in the long term (with the rest on hillsides or in power plants). Since rooftops will exist regardless of whether solar-PV is used, that portion is not included in the footprint or spacing calculations discussed shortly.

6.6. Coal-CCS, Geothermal, Hydroelectric

The land required for coal-CCS includes the lands for the coal plant facility, the rail transport, and the coal mining. A 425 MW coal-CCS plant requires a total of about 5.2 km^2 (Appendix), or about 1.2 km^2 per 100 MW. The land required for a 100 MW geothermal plant is about 0.34 km^2 (Appendix). A single reservoir providing water for a 1300 MW hydroelectric power plant requires about 650 km^2 (Appendix), or 50 km^2 per 100 MW installed.

6.7. Footprint and Spacing for Onroad Vehicles

Here, we compare the footprint and spacing areas required for each technology to power all onroad (small and large) vehicles in the United States. All numbers are derived in the Appendix. Wind-BEVs require by far the least footprint on the ground over land or ocean (1-2.8 km^2). Tidal-BEVs do not consume ocean surface or land area but would require about 121-288 km^2 of ocean floor footprint. Wave devices would require about 400-670 km^2 of ocean surface footprint to power U.S. BEVs. Corn ethanol, on the other hand, would require 900,000-1,600,000 km^2 (223-399 million acres) just to grow the corn for the fuel, which compares with a current typical acreage of harvested corn in the U.S. before corn use for biofuels of around 75 million[77]. Cellulosic ethanol could require either less or more land than corn ethanol, depending on the yield of cellulosic material per acre. An industry estimate is 5-10 tons of dry matter per acre[78]. However, a recent study based on data from established switchgrass fields gives 2.32-4.95 tons/acre[79]. Using the high and low ends from both references suggests that cellulosic ethanol could require 430,000-3,240,000 km^2 (106-800 million acres) to power all U.S. onroad vehicles with E85.

Figure 5 shows the ratio of the footprint area required for each technology to that of wind-BEVs. The footprint area of wind-BEVs is 5.5-6 orders of magnitude less than those of corn- or cellulosic-E85, 4 orders of magnitude less than those of CSP- or PV-BEVs, 3 orders of magnitude less than those of nuclear- or coal-BEVs, and 2-2.5 orders of magnitude less than those of geothermal-, tidal-, or wave-BEVs. The footprint for wind-HFCVs is about 3 times that for wind-BEVs due to the larger number of turbines required to power HFCVs than BEVs. As such, wind-BEVs and wind-HFCVs are by far the least invasive of all technologies over land. The relative ranking of PV-BEVs with respect to footprint improves relative to that shown in the figure (going ahead of CCS-BEV) if >80% (rather than the 30% assumed) of all future PV is put on rooftops.

Figure 5. Ratio of the footprint area on land or water required to power all vehicles in the U.S. in 2007 by a given energy technology to that of wind-BEVs. The footprint area is the area of the technology touching the ground, the ocean surface, or the ocean floor. Also shown are the ratios of the land areas of California and Rhode Island to the footprint area of wind-BEVs. Low and high values are shown for each technology/state.

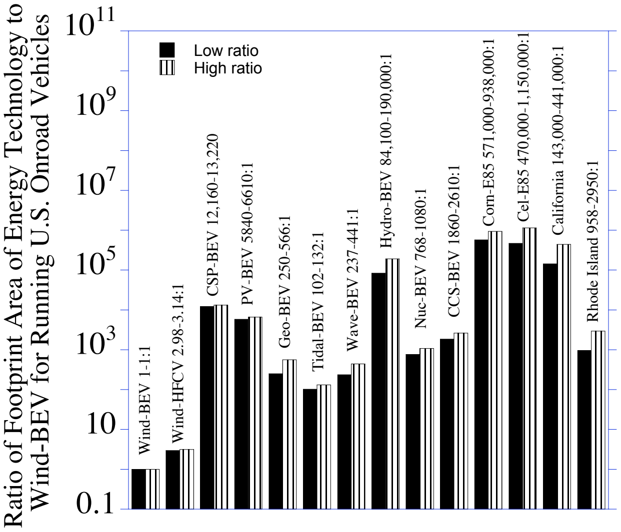
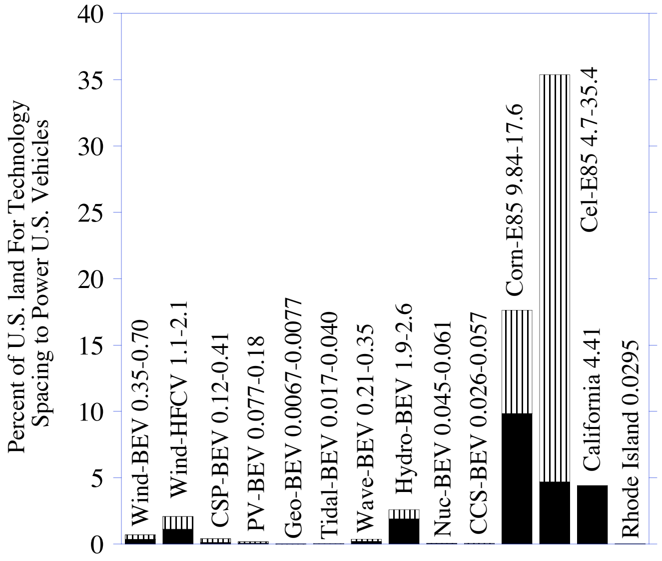


Figure 6 compares the fractional area of the U.S. (50 states) required for spacing (footprint plus separation area for wind, tidal, wave, nuclear; footprint area for the others) needed by each technology to power U.S. vehicles. The array spacing required by wind-BEVs is about 0.35-0.7% of all U.S. land, although wind turbines can be placed over land or water. For wind-HFCVs, the area required for spacing is about 1.1-2.1% of U.S. land. Tidal-BEVs would not take any ocean surface or land area but would require 1550-3700 km^2 of ocean floor for spacing (5-6% that of wind) or the equivalent of about 0.017-0.04% of U.S. land. Wave-BEVs would require an array spacing area of 19,000-32,000 km^2 (about 50-59% that of wind), or an area equivalent to 0.21-0.35% of U.S. land. Solar-PV powering U.S. BEVs requires 0.077-0.18% of U.S. land for spacing (and footprint), or 19-26% of the spacing area required for wind-BEVs. Similarly, CSP-BEVs need about 0.12-0.41% of U.S. land or 34-59% of the spacing required for wind-BEV.

Figure 6. Low (solid) and high (solid+lines) fractions of U.S. land area (50 states) required for the spacing (footprint plus separation area for wind, tidal, wave, and nuclear; footprint area only for the others) of each energy technology for powering all U.S. vehicles in 2007. Also shown are the fractions of U.S. land occupied by California and Rhode Island. Multiply fractions by the area of the U.S. (9,162,000 km^2) to obtain area required for technology.



A 100 MW geothermal plant requires a land area of about 0.33 km^2. This translates to about 0.006-0.008% of U.S. land for running all U.S. BEVs, or about 1.1-1.6% the array spacing required for wind-BEVs. Powering all onroad vehicles in the U.S. with nuclear power would require about 0.045-0.061% of U.S. land for spacing, or about 9-13% that of wind-BEVs. The land required for CCS-BEVs is 0.03-0.06% of the U.S., or about 7.4-8.2% of the array spacing required for wind-BEVs. The land required for hydro-BEVs is significant but lower than that for E85. Hydro-BEV would require about 1.9-2.6% of U.S. land for reservoirs. This is 3.7-5.4 times larger than the land area required for wind-BEV spacing. Corn and cellulosic ethanol require by far the most land of all the options considered here. Running the U.S. onroad vehicle fleet with corn-E85 requires 9.8-17.6% of all 50 U.S. states, or 2.2-4.0 States of California. Cellulosic-E85 would require from 4.7-35.4% of U.S. land, or 1.1-8.0 States of California, to power all onroad vehicles with E85.

In sum, technologies with the least spacing area required are, in increasing order, geothermal-BEVs, tidal-BEVs, wave-BEVs, CCS-BEVs, nuclear-BEVs, PV-BEVs, CSP-BEVs, wave-BEVs, and wind-BEVs. These technologies would all require <1% of U.S. land for spacing. Corn-E85 and cellulosic-E85 are, on the other hand, very land intensive. The spacing area required for wind-BEVs is about 1/26 that required for corn-ethanol (E85) and 1/38 that required for cellulosic ethanol (E85), on average. The spacing area for PV-BEVs is about 1/3 that of wind-BEVs.

7. Water supply

Water shortages are an important issue in many parts of the world and may become more so as air temperatures rise from global warming. Here, energy technologies are examined with respect to their water consumption (loss of water from water supply) when the technologies are used to power U.S. vehicles. Results are summarized in Figure 7 and derived in the Appendix.

7.1. Corn- E85

For corn-E85, water is used for both irrigation and ethanol production. Most water for corn comes from rainfall, but in 2003, about 13.3% (9.75 million out of the 73.5 million acres) of harvested corn in the U.S. was irrigated. With 1.2 acre-feet of irrigation water per acre of land applied to corn[80], an average of 178 bushels per acre[80], and 2.64 gallons of ethanol per bushel, the water required for growing corn in 2003 was about 832 gallons per gallon of ethanol produced from irrigated land, or 102.3 gal-H_2O/gal-ethanol for all (irrigated plus nonirrigated) corn. In Minnesota ethanol factories, about 4.5 L of water were required to produce one liter of 100% ethanol in 2005[81]. Much of the water consumed is from evaporation during cooling and wastewater discharge. Thus, the irrigation plus ethanol-factory water requirement for corn ethanol in the U.S. is about 107 gal-H_2O/gal-ethanol, on average. This compares with an estimate for an earlier year with a higher fraction of irrigated corn of 159 gal-H_2O/gal-ethanol[82].

7.2. Cellulosic-E85

The use of switchgrass to produce ethanol would most likely reduce irrigation in comparison with use of corn. However, since agricultural productivity increases with irrigation (e.g., irrigated corn produced 178 bushels per harvested acre in the U.S. in 2003, whereas irrigated+nonirrigated corn produced 139.7 bushels per harvested acre[77]), it is likely that some growers of switchgrass will irrigate to increase productivity. Here, it is assumed that the irrigation rate for switchgrass will be half that of corn (thus, around 6.6% of switchgrass crops may be irrigated).

7.3. Hydroelectric

Hydroelectric power consumes water as a result of evaporation from the surface of reservoirs. Since reservoirs are also designed to conserve water and provide flood control, irrigation, navigation and river regulation, salinity control in delta regions, and domestic water supply, not all evaporation can be attributable to hydroelectricity. An estimate of water consumption through evaporation from reservoirs by hydroelectric power that accounted for river and stream evaporation but not for loss to the ocean or for other uses of reservoir water is 18 gal/kWh[83]. We multiply this number by the fraction of a reservoir's use attributable to hydroelectricity. Although several big reservoirs were built primarily for power supply, they are currently used for the purposes described above. As such, their fraction attributable to hydroelectricity should be less than or equal to their capacity factor (25-42%, Table 1), which gives the fraction of their turbines' possible electrical output actually used. The main reason capacity factors are not near 100% is because water in the dam is conserved for use at different times during the year for the purposes listed. We thus estimate the water consumption rate as 4.5-7.6 gal/kWh.

7.4. Nuclear

Nuclear power plants, usually located near large bodies of surface water, require more water than other fossil-fuel power plants[84] but less water than ethanol production. Water is needed in a nuclear plant to produce high-pressure steam, which is used to turn a turbine to drive a generator. Most water is returned at higher temperature to is source, but some of the water is lost by evaporation. The water consumption (from evaporation) in a nuclear power plant ranges from 0.4-0.72 gal/kWh, depending on the type of cooling technology used[84].

7.5. Coal-CCS

Carbon capture and sequestration projects result in water consumption due to the coal plant, estimated as 0.49 gal/kWh[85]. The increased electricity demand due to the CCS equipment is accounted for by the fact that more kWh of electricity are required, thus more water is consumed, when CCS equipment is used.

7.6. CSP

Concentrated solar power with parabolic trough technology requires the heating of water to produce steam. However, since the process is closed-loop, this water is generally not lost. However, the steam needs to be recondensed for water reuse. This is generally done by combining the steam with cooler water in a cooling tower or by air cooling in a heat exchanger. In the case of water cooling, water is lost by evaporation. Water is also needed to clean mirrors. One estimate of the water consumption for parabolic-trough CSP during is 0.74 gal-H_2O/kWh for water cooling and 0.037 gal-H_2O/kWh for mirror cleaning[86]. The water consumption for central-tower receiver CSP cooling and cleaning is 0.74 gal-H_2O/kWh[86]. If air cooling is used, water use decreases significantly, but efficiency also decreases. We assume here that CSP will be water cooled to maximize efficiency. For parabolic dish-shaped reflectors, only water for cleaning is needed.

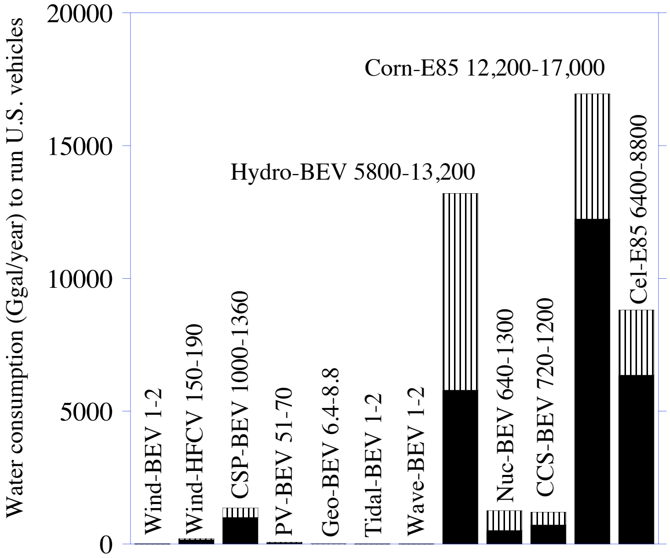
7.7. Geothermal, Wind, Wave, Tidal, Solar-PV

Geothermal plants consume some water during their construction and operation. One estimate of such consumption is 0.005 gal/kWh[27]. Wind turbines, wave devices, and tidal turbines do not consume water, except in the manufacture of the devices. An estimate of water consumption due to wind is 0.001 gal-H_2O/kWh[85]. We assume the same for wave and tidal device manufacturing. Solar-PV requires water for construction of the panels and washing them during operation. We estimate the water consumption during panel construction as 0.003 gal-H_2O/kWh and that during cleaning the same as that for CSP, 0.037 gal-H_2O/kWh, for a total of 0.04 gal-H_2O/kWh.

7.8. Comparison of Water Consumption

Figure 7 compares the water consumed by each technology when used to power all U.S. onroad vehicles. When wind or any other electric power source is combined with HFCVs, additional water is required during electrolysis to produce hydrogen (through the reaction $H_2O\text{+electricity} \rightarrow H_2 + 0.5\ O_2$). This consumption is accounted for in the wind-HFCVs bar in the figure. The lowest consumers of water among all technologies are wind-BEVs, tidal-BEVs, and wave-BEVs, followed by geo-BEVs, PV-BEVs, and wind-HFCVs. The largest consumer is corn-E85, followed by hydro-BEVs and cellulosic-E85. If all U.S. onroad vehicles were converted to corn-E85, an additional 8.2-11.4% of the total water consumed for all purposes in the U.S. in 2000 would be needed. For cellulosic-E85, an additional 4.3-5.9% would be needed (subject to the uncertainty of the irrigation rate). Since hydroelectricity is unlikely to expand significantly rather than be used more effectively to provide peaking power, its additional water consumption is not such an issue. Further, because new dams built for the joint purposes of water supply and hydroelectricity will enhance the availability of water in dry months, an additional advantage exists to hydroelectric power with respect to water supply that is not captured in Figure 7.

Figure 7. Low (solid) and high (solid+lines) estimates of water consumption (Gigagallons/year) required to replace all U.S. onroad vehicles with other vehicle technologies. Consumption is net loss of water from water supply. Data for the figure are derived in the Appendix. For comparison, the total U.S. water consumption in 2000 was 148,900 Ggal/year[87].



8. Effects on Wildlife and the Environment

The effects of energy technologies on wildlife and natural ecosystems are proportional to the footprint on land or water required by the technology, the air and water pollution caused by the technology, and direct interactions of wildlife with the technology. In this section, we rank the different technologies based on these effects.

The covering of land with a building or paved road, or the surface mining of land effectively destroys habitat. For example, between 1992 and 2002, 381,000 acres (1542 km^2) of U.S. forest habitat were destroyed by mountaintop removal due to coal mining[88]. With coal-CCS, mountaintop removal will increase as coal consumption expands to meet new energy demand and power CCS equipment.

The conversion of land from natural vegetation to cropland, needed for the production of biofuels, similarly reduces available habitat, particularly when pesticides are used to protect crops. This effect is greatest when rich ecosystems, such as a tropical or other forests are destroyed either directly for biofuel farming or indirectly when biofuel farming in other areas causes cattle ranchers or soy farmers to move and clear rainforest areas. Even when agricultural land is converted from one type of crop to another, biota may be lost. For example, when switchgrass replaces a non-biofuel crop, switchgrass' lignocellulose is removed to produce ethanol, so microorganisms, which normally process the lignocellulose, cannot replenish soil nutrients, reducing biota in the soil. On the other hand, good selection of land use for growing biofuel crops could reduce impacts of the crops on the local ecosystem[60].

Dams for hydroelectric power reduce salmon population by reducing access to spawning grounds. To mitigate this problem, fish ladders are usually installed. Because sediment builds up behind a dam, water leaving a dam contains little sediment[89]. This can lead to scavenging of sediment from riverbeds downstream, causing loss of riverbank habitat. On the other hand, the flooding of land with water behind a dam reduces habitat for land-based wildlife but increases it for aquatic wildlife there. Similarly, the addition of structures to the ocean increases the surface area of artificial reefs, increasing the presence of fish life in these areas[90]. The use of dams for peaking power also affects the diurnal variation of water flow down a river. This can affect downstream ecosystems negatively in some cases although the effect may vary significantly from river to river.

In ranking the relative impacts of land use change due to the technologies on wildlife, we consider the footprint of the technology on land based on Figure 5, but take into account whether the land was converted to water, agricultural land, land-based buildings/structures, or ocean-based structures, or mined on its surface and what the previous land use might have been. In the case of solar-PV, for example, the impacts are proportional to the footprint area in Figure 5 (which already excludes rooftops), but less proportional to footprint than other energy sources since much of PV in the near future will be located in arid regions with less wildlife displaced than for other technologies, which will be situated on more biodiverse land. CSP will similarly be located in more arid land. As a result, the rankings of CSP and PV with respect to wildlife in Table 4 are higher than their respective footprint rankings.

Air-pollution-relevant emissions harm animals as much as they damage humans[91]. Such emissions also damage plants and trees by discoloring their leaves, stunting their growth, or killing them[92-94]. To account for air pollution effects on wildlife and ecosystems, we use the information from Figure 4, which shows the effects of the energy technologies on human air pollution mortality, as a surrogate.

The effects on bird and bat deaths due to each energy technology should also be considered. Energy technologies kill birds and bats by destroying their habitat, polluting the air they breathe and the water they drink, and creating structures that birds and bats collide with or are electrocuted on. Loss of habitat is accounted for here by considering the footprint of each technology on the ground. Figure 5 indicates that a large penetration of wind turbines for BEVs or HFCVs will result in 2.5-orders-of-magnitude less habitat loss based on footprint than geothermal power and 3 orders-of-magnitude less than Nuc-BEVs or CCS-BEVs. In particular, mountaintop removal during coal mining is historically responsible for the decline in several bird species, including the Cerulean Warbler, the Louisiana Waterthrush, the Worm-Eating Warbler, the Black-and-White Warbler, and the Yellow-Throated Vireo[88]. Although CSP and PVs require more footprint than most other technologies, both will be located primarily in deserts or, in the case of PV, also on rooftops, reducing their effects on habitat. The large footprint requirements for corn and cellulosic ethanol will cause the largest loss in bird habitat, such as wetlands, wet meadows, grassland, and scrub[88].

With regard to air pollution, the low air pollution emissions and human mortality associated with wind-BEVs (Figure 4) suggest it will have the least effect on respiratory- and cardiovascular-related bird and bat mortality. Corn- and cellulosic-E85 will have the greatest impact, followed by CCS-BEVs and nuclear-BEVs.

Because significant concern has been raised with respect to the effect of wind turbines on birds and bat collisions, we examine this issue in some detail. With regards to structures, wind turbines in the U.S. currently kill about 10,000-40,000 birds annually, 80% of which are songbirds and 10%, birds of prey[88]. For comparison, 5-50 million birds are killed annually by the 80,000 communication towers in the U.S. [88]. Birds are attracted by their lights and collide with them or their guy wires during night migration. Also, 97.5-975 million birds are killed by collision with windows and hundreds of millions of birds are killed by cats in the U.S. each year[88]. Finally, in 2005, 200 million birds were lost to the Avian Flu worldwide[95]. A recent report determined that less than 0.003% of anthropogenic bird deaths in 2003 were due to wind turbines in four eastern U.S. states[96]. If 1.4-2.3 million 5-MW wind turbines were installed worldwide to eliminate 100% of anthropogenic CO_2 emissions (Appendix), the number of bird deaths worldwide due to wind would be about 1.4-14 million, less than 1% of the global anthropogenic bird loss. However, such a conversion would simultaneously eliminate global warming, air pollution human and animal mortality due to current energy use.

A related issue is the effect of tidal turbine rotors on sea life. Because tidal turbine rotors do not turn rapidly, they should not endanger sea life significantly. Further, with tidal turbine configurations that use a duct to funnel water[97], it may be possible to put a grating in front of the duct to prevent medium- and large-sized fish from entering the duct. The turbines may enhance sea communities by serving as artificial reefs as offshore wind turbines do[90].

Some additional effects of energy technologies include thermal and chemical pollution, radioactive waste disposal, and feedbacks of technologies to the atmosphere. Thermal pollution reduces dissolved oxygen in water directly and indirectly by enhancing algae blooms. A reduction in dissolved oxygen harms fish, amphibians, and copepods. Thermal pollution also increases the rate of aquatic life metabolism, increasing competition for food. The energy technologies considered here that impact the temperature of water in lakes and rivers the most are CSP, nuclear, coal-CCS, and ethanol – the first three directly and the last through its lifecycle requirement of coal and nuclear electricity. The remaining technologies affect thermal pollution proportionally to their lifecycle CO_2e emissions, most of which come from thermal power plants as well, but such lifecycle energy requirements are small.

Chemical waste pollution into surface and groundwater also impacts wildlife. Ethanol factories produce sewage-like effluent containing syrup, ethanol, chloride, copper, and other contaminants, produced during fermentation and distillation[98]. Coal-CCS releases acids (SO_2 and NO_x) and mercury into the air that deposit to lakes and rivers as acid deposition. Some CCS technologies produce liquid wastes that are discharged to lakes or rivers and solid wastes that are incinerated. Both coal- and uranium-mining operations result in the release of chemicals into ground and surface waters. Other energy options are assumed to emit chemical waste proportionally to their lifecycle emissions.

Nuclear power plants produce fuel rods that are usually stored on site for several years in cooling ponds pending transport to a permanent site. The local storage of this "high-level waste" may preclude the future re-use of some nuclear power plant land for decades to centuries. In the U.S., a planned permanent site since 1982 has been Yucca Mountain. However, studies are still being carried out to determine whether storage at this site poses a long-term hazard[99]. Nuclear power plants also produce low-level waste, including contaminated clothing and equipment.

Finally, a question that frequently arises is the effect of a large penetration of wind turbines on local and global meteorology. This issue can be examined correctly only with high-resolution computer modeling. To date, no resolved study covering the large scale has been performed. The modeling studies that have been performed are too coarse for their results to be relied on. A back-of-the-envelope calculation of the effects that accounts for the upstream and downstream velocity of a turbine and the global mean of measured winds over land indicates that, if 10 million 1.5 MW wind turbines were used to power all the world's energy (electric plus nonelectric), the combined energy loss from the slower winds among all wakes worldwide in the boundary layer (about 1 km) would be less than 1%[100].

9. Energy Supply Disruption

Another key question for each energy technology is the extent to which the supply of energy from it can be disrupted by terrorism, war, or natural disaster. The energy technologies that are distributed (e.g., solar PV, wind, wave, and tidal) are least prone to disruption, whereas those that are centralized (e.g., nuclear, coal-CCS, hydroelectric, geothermal, CSP, ethanol factories) are most at risk to disruption[101].

Severe weather, earthquake, fire, flood, or terrorist activity can take out some distributed-energy devices, but it is unlikely that an entire wind or solar PV farm could be disrupted by one of these events. With respect to severe weather, the survival wind speed for most wind turbines is around 60-65 m/s, within range of the wind speeds in a Category 4 hurricane of 58.5-69 m/s. Most tornados are less than 100 m across. An F4 (92.5-116 m/s) tornado can reach 0.5-1.6 km wide. An F5 (wind speeds 117-142 m/s) can reach 1.6-5 km wide. Although the chance that a Category 4-5 hurricane or an F4-F5 tornado hits a wind turbine is small, efforts could be made to strengthen turbines in at-risk areas.

In the case of centralized power sources, the larger the plant, the greater the risk of terrorism and collateral damage. In the case of nuclear power, collateral damage includes radiation release. In the case of hydroelectric power, it includes flooding. In the case of ethanol and coal-CCS, it includes some chemical releases. Whereas, nuclear power plants are designed to withstand tornados and other severe whether, the other power plants are not. However, nuclear power plants are vulnerable to heat waves. Because nuclear power plants rely on the temperature differential between steam and river or lake water used in the condenser, they often cannot generate electricity when the water becomes too hot, as occurred during the European heat wave of 2004, when several nuclear reactors in France were shut down.

Because nuclear power plants are centralized, release radiation if destroyed, and may shut down during a heat wave, we deem them to be the most likely target of a terrorist attack and prone to energy supply disruption among all energy sources. Large hydroelectric power plants are the second-most likely to be targeted by terrorists. Because they are a centralized power source and susceptible to reduced capacity during a drought, they are also considered to be the second-most vulnerable to disruption. Ethanol factories, coal-CCS, geothermal, and CSP plants are all centralized so are also subject to disruption and attack, but less so than nuclear or hydroelectricity. The greater potential for chemical releases from an ethanol plant makes it more risky than the other energy sources. CSP plants are generally smaller than coal-CCS plants, so are less likely to result in a disruption if disabled. The distributed-energy sources are the least likely to be disrupted. Among these, tidal power may be the most protected from severe weather whereas wave power, the most vulnerable. Solar PVs are least likely to be sited in locations of severe storms, so will be disrupted less than wind. Wind-BEV supply is more secure than wind-HFCV supply since fewer turbines are required in the former case.

10. Intermittency and How to Address It

Wind, solar, wave, and tidal power at one location and time are naturally intermittent. In other words, at a single location and time, it is not possible to guarantee power from them. Tidal power at a single location and time is more reliable because of the predictability of the tides. Solar intermittency is due to day-night and seasonal transitions of the sun and clouds. Wind intermittency is due to variations in pressure gradients over minutes to seasons to years. With the large-scale deployment of an intermittent resource today, backup generators are needed that can be brought online quickly, increasing stress and maintenance of the system. However, it is shown here that when intermittent energy sources are combined with each other or over large geographical regions, they are much less intermittent than at one location. When combined with storage media, such as batteries or hydrogen, the effect of their intermittency is reduced further or eliminated.

Coal-CCS, nuclear, geothermal, and hydroelectric power are more reliable than the resources listed above but have scheduled and unscheduled outages. For example, nuclear power plants have unscheduled outages during heat waves (Section 9). Further, the average coal plant in the U.S. from 2000-2004 was down 6.5% of the year for unscheduled maintenance and 6.0% of the year for scheduled maintenance[102]. This compares with a total down time for modern wind turbines of 0-2% over land and 0-5% over the ocean[90]. Solar-PV panels similarly have a downtime of near 0-2%. A difference between the outages of centralized and distributed plants is that when individual solar panels or wind turbines are down, for example, only a small fraction of electrical production is affected, whereas when a nuclear or coal plant is down, a large fraction is affected. Nuclear plants in the U.S. have become more reliable in the last decade. In 2006, the overall capacity factor for nuclear in the U.S. was 89.9%[103] compared with 80.8% worldwide (Table 1). Hydroelectric power plants are more reliable than most other centralized plants (e.g., with unscheduled outage rates of <5%[102]; however, because they are often used for peaking, their average capacity factors are low (Table 1). Geothermal capacity factors in the U.S. are generally 89-97%[27], suggesting a reliability similar to nuclear power. Like with nuclear, the globally-averaged capacity factor of geothermal is lower than its U.S. average (Table 1). The overall outage rate of CSP plants in the Mojave desert have been reported as 3.3-4.0% for 1997-2001, except for 2000 when the outage rate was 7.1%[104].

Whether or not intermittency affects the power supply depends on whether effort to reduce intermittency are made. Five methods of reducing intermittency or its effects are (a) interconnecting geographically-disperse naturally-intermittent energy sources (e.g., wind, solar, wave, tidal), (b) using a reliable energy source, such as hydroelectric power, to smooth out supply or match demand, (c) using smart meters to provide electric power to vehicles in such a way as to smooth out electricity supply, (d) storing the electric power for later use, and (e) forecasting the weather to plan for energy supply needs better. These are discussed briefly, in turn.

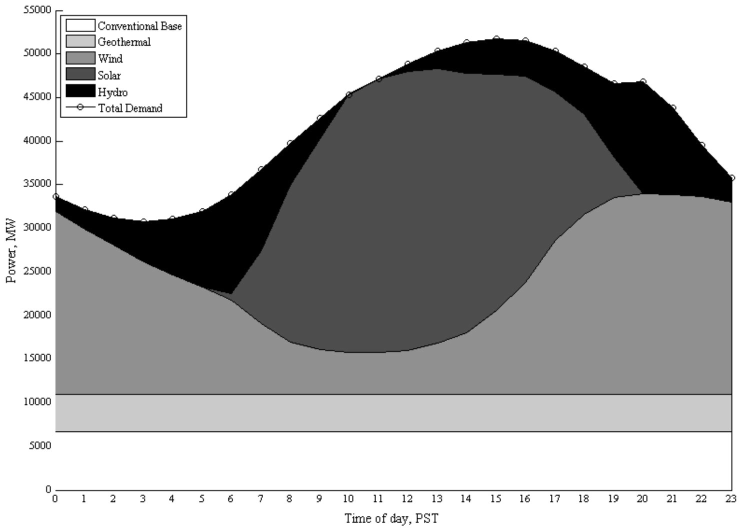
10a. Interconnecting Geographically-Dispersed Intermittent Energy Sources

Interconnecting geographically-disperse wind, solar, tidal, or wave farms to a common transmission grid smoothes out electricity supply significantly, as demonstrated for wind in early work[105]. For wind, interconnection over regions as small as a few hundred kilometers apart can eliminate hours of zero power, accumulated over all wind farms and can convert a Rayleigh wind speed frequency distribution into a narrower Gaussian distribution[106]. When 13-19 geographically-disperse wind sites in the Midwest, over a region 850 km x 850 km, were hypothetically interconnected, an average of 33% and a maximum of 47% of yearly-averaged wind power was calculated to be usable as baseload electric power at the same reliability as a coal-fired power plant[107]. That study also found that interconnecting 19 wind farms through the transmission grid allowed the long-distance portion of capacity to be reduced, for example, by 20% with only a 1.6% loss in energy. With one wind farm, on the other hand, a 20% reduction in long-distance transmission caused a 9.8% loss in electric power. The benefit of interconnecting wind farms can be seen further from real-time minute-by-minute combined output from 81% of Spain's wind farms[108]. Such figures show that interconnecting nearly eliminates intermittency on times scales of hours and less, smoothing out the electricity supply. In sum, to improve the efficiency of intermittent electric power sources, an organized and interconnected transmission system is needed. Ideally, fast wind sites would be identified in advance and the farms would be developed simultaneously with an updated interconnected transmission system. The same concept applies to other intermittent electric power sources, such as PV and CSP. Because improving the grid requires time and expense, planning for it should be done carefully.

10b. Load smoothing or matching with hydroelectric or geothermal power

A second method of reducing the effect of intermittency of wind is to combine multiple renewable energy sources[109], including wind, solar, hydroelectric, geothermal, tidal, and wave power, together, to reduce overall intermittency, and to use hydroelectric or geothermal power to fill in the gaps. This concept is illustrated for California in Figure 8. Because hydroelectric power, when run in spinning reserve mode, can be increased or decreased within 15-30 seconds, it is an ideal source of peaking power. Hydroelectric power is used significantly for peaking rather than baseload power today, so enhancing its use for peaking should not be a large barrier. Geothermal power is used primarily as a baseload source. However, geothermal plants can be designed to follow load as well[110].

Figure 8. Example of powering 80% of California's July electricity with load-matching renewables in 2020. The renewables include wind (26,425 MW installed, 8443 MW generated), solar-PV without storage (39,828 MW installed, 12,436 MW generated), geothermal (4700 MW installed, 4324 MW generated), and hydroelectric (13,500 MW installed - the current installation, 9854 MW generated). Hydroelectric is used to fill in gaps, as it currently does in California. Other baseload sources are assumed to supply 20% of electricity. The top line is the monthly-averaged power demand estimated for July, 2020, from California Energy Commission data. January demand is much lower (peaking at 37,000 MW) and is met by higher wind production offsetting lower solar production. Figure from Ref. 111 using wind data from model calculations at five locations in California[34].



10c. Using smart meters to provide electric power for vehicles at optimal times

A third method of smoothing intermittent power is to upgrade smart meters[112] to provide electricity for electric vehicles when wind power supply is high and to reduce the power supplied to vehicles when wind power is low. Utility customers would sign up their electric vehicles under a plan by which the utility controlled the nighttime (primarily) or daytime supply of power to the vehicles. Since most electric vehicles would be charged at night, this would provide primarily a nighttime method of smoothing out demand to meet supply.

10d. Storage

A fourth method of dealing with intermittency is to store excess intermittent energy in batteries (e.g., for use in BEVs), hydrogen gas (e.g., for use in HFCVs), pumped hydroelectric power, compressed air (e.g., in underground caverns or turbine nacelles), flywheels, or a thermal storage medium (as done with CSP). One calculation shows that the storage of electricity in car batteries, not only to power cars but also to provide a source of electricity back to the grid (vehicle-to-grid, or V2G), could stabilize wind power if 50% of U.S. electricity were powered by wind and 3% of vehicles were used to provide storage[113]. The only disadvantage of storage for grid use rather than direct use is conversion losses in both directions rather than in one.

10e. Forecasting

Finally, forecasting the weather (winds, sunlight, waves, tides, precipitation) gives grid operators more time to plan ahead for a backup energy supply when an intermittent energy source might produce less than anticipated. Forecasting is done with either a numerical weather prediction model, the best of which can produce minute-by-minute predictions 1-4 days in advance with good accuracy, or with statistical analyses of local measurements. The use of forecasting reduces uncertainty and improves planning, thus reduces the relevance of intermittency.

We rank each energy technology combination in terms of intermittency based on the scheduled and unscheduled downtime of the electric power source, whether the downtime affects a large or small fraction of electric power generation, the natural intermittency of the electric power source, and whether the technology combination includes a storage medium. For example, all cases considered involve combinations of the technology with either BEVs, HFCVs, or E85. Since BEVs are charged over a several-hour period, the instantaneous electricity production is not so important when the aggregate production over the period is guaranteed. With HFCVs, the hydrogen fuel is produced by electrolysis and can be stored for months to years. Thus, neither instantaneous nor weekly or seasonal fluctuations are necessarily disadvantageous. Since E85 can be stored, intermittency of its production is similarly not so much of an issue. Based on the low downtime of wind turbines, the fact that downtime affects only a small portion of the source, and the fact that intermittency is irrelevant for the production of hydrogen, we rank wind-HFCVs as the most reliable of all potential energy technology combinations. Because of the low outage rate and the ability to turn hydroelectric power on and off when it is in spinning reserve mode within 15-30 seconds, hydro-BEVs are ranked the second-most reliable of all energy technology combinations.

Because E85 can be stored, its production is generally independent of short-term intermittency. However, because ethanol plants are subject to fluctuations in crop supplies due to variations in weather and are more susceptible than hydroelectric power or wind turbines to planned or unplanned outages, corn- and cellulosic-E85 are tied for third. The remaining combinations involve production of electricity for BEVs. CSP-BEVs are ranked fifth because of CSP's ability to store energy in thermal storage media on-site and their low overall outage rate (< 5%). Although geothermal, nuclear, and coal-CCS can supply electricity in winter better than CSP-BEVs, the outage rates for the former technologies are higher, thus they are ranked 6th-8th, respectively. Tidal power is somewhat predictable, thus tidal-BEVs are ranked 9th. Wind-BEVs, PV-BEVs, and wave-BEVs are more intermittent[114,115]. If wind peaks at night, such as over land in many places, PV can match daytime peak loads better than wind[114] (e.g., Figure 8). However, for powering BEVs, most demand will be at night. Further, offshore wind and wave power generally peak during the time of peak demand. As such, we rank PV-BEVs, wind-BEVs, and wave-BEVs the same in terms of reliability. As discussed, the reliability of the intermittent technologies can be improved or ensured with the four methods discussed in this section; the rankings do not reflect such potential improvements.

13. Overall Results

Table 4 ranks each of 12 technology combinations for running U.S. vehicles in terms of 11 categories considered, then weights each ranking by the relative importance of each category to obtain an overall ranking of the technology combination. The weights ensure that effects on CO$_2$e emissions and mortality are given the highest priority. The third priority is footprint on the ground combined with spacing, followed by the combination of reliability plus energy supply disruption, then water consumption and resource availability, then the combination of effects on wildlife plus water chemical and thermal pollution. Sensitivities of results to the weights are discussed shortly.

The rankings for each category are referenced in the footnote of the table and were discussed previously, except not completely with respect to resource availability. With respect to resource availability, we consider the technical potential of the resource from Table 1, whether the spread of the technology to a large scale is limited by its footprint land area from Figure 5, and the difficulty of extracting the resource. Based on these criteria, PV-BEVs are ranked the highest in terms of resource because solar-PV has the greatest overall resource availability without the need to extract the resource from the ground and is not limited by area for supplying a substantial portion of U.S. power. Wind-BEVs and wind-HFCVs are ranked second and third, respectively, since wind is the second-most-abundant natural resource, wind does not require extraction from the ground, and wind's footprint area is trivial. CSP-BEVs are ranked fourth due to the great abundance of solar. They are behind PV-BEVs and the wind technologies due to the greater footprint required for CSP-BEVs. Wave- and tidal-BEVs follow due to the renewable nature of their resource and their small footprint. Geo-BEVs are next, since they require extraction from the ground and the resource (heat from the earth) can dissipate at a given location although it will replenish over time. CCS-BEVs and nuclear-BEVs follow due to their abundant, although limited resource, but with the need to extract the resource from the ground, transport it, and process it. Hydro-BEVs are limited by the land required for reservoirs. Similarly, corn-E85 and cellulosic-E85 are limited by their significant land requirements, with cellulosic ethanol potentially requiring more land than corn ethanol (Figures 5 and 6).

Table 4. Ranking (from 1-12, with 1 being the best) over individual categories and among all categories of each energy technology combination when used to power all U.S. onroad vehicles. The ranking of each technology for each category is then multiplied by its weight (second column) to obtain a weighted-average ranking, which is analogous to a score from 1-12. The numerical order of the overall rank is then given (bottom row). The weights sum up to 100%.

	Weight (%)	Wind -BEV	Wind-HFCV	PV-BEV	CSP-BEV	Geo-BEV	Hydro-BEV	Wave -BEV	Tidal-BEV	Nuc-BEV	CCS-BEV	Corn -E85	Cel-E85
[a]Resource abundance	10	2	3	1	4	7	10	6	5	9	8	11	12
[b]CO$_2$e emissions	22	1	3	5	2	4	8	7	6	9	10	12	11
[c]Mortality	22	1	3	5	2	4	8	7	6	10	9	11	12
[d]Footprint	12	1	2	8	9	5	10	4	3	6	7	11	12
[e]Spacing	3	8	9	5	6	2	10	7	1	4	3	11	12
[f]Water consumption	10	1	6	5	9	4	11	1	1	7	7	12	10
[g]Effects on wildlife	6	1	3	5	2	4	8	7	6	9	10	11	12
[h]Thermal pollution	1	1	2	4	8	3	7	6	5	12	11	10	9
[i]Water chemical pollution/ radioactive waste	3	1	3	5	2	4	8	7	6	10	9	12	11
[j]Energy supply disruption	3	3	4	2	6	7	11	5	1	12	8	9	9
[k]Normal operating reliability	8	10	1	10	5	6	2	10	9	7	8	3	3
Weighted Average		2.09	3.22	5.26	4.28	4.60	8.40	6.11	4.97	8.50	8.47	10.6	10.7
Overall rank		1	2	6	3	4	8	7	5	9-tie	9-tie	11	12

a) Based on Table 1, Figure 5, and discussion in Section 13; b) Based on Figure 2; c) Based on Figure 4; d) Based on Figure 5; e) Based on Figure 6, except that tidal was placed ahead of geothermal since the spacing area on the sea floor is not so relevant (although footprint area is); f) Based on Figure 7; g) Based primarily on footprint area, air pollution emissions, and collision risk, as described in Section 8; h) Based on discussion of thermal pollution in Section 8; i) Based on the discussion of chemical pollution and radioactive waste in Section 8; j) Based on discussion in Section 9; k) Based on discussion in Section 10.

From the overall rankings in Table 4, four general tiers of technology options emerge based on distinct divisions in weighted average score of the technology. Tier 1 (<4.0), includes wind-BEVs and wind-HFCVs. Tier 2 (4.0-6.5) includes CSP-BEVs, Geo-BEVs, PV-BEVs, tidal-BEVs, and wave-BEVs. Tier 3 (6.5-9) includes hydro-BEVs, nuclear-BEVs, and CCS-BEVs. Tier 4 (>9) includes corn- and cellulosic-E85.

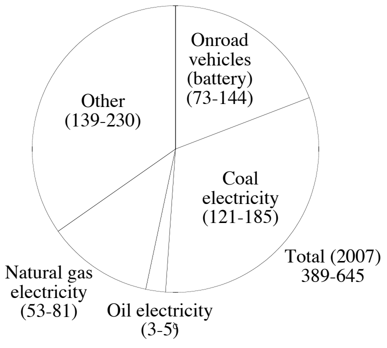
Wind-BEVs rank first in seven out of 11 categories, including the two most important, mortality and climate damage reduction. Although HFCVs are less efficient than BEVs, wind-HFCVs still provides a greater benefit than any other vehicle technology. The Tier 2 combinations all provide outstanding benefits with respect to climate and mortality. The Tier 3 technologies are less desirable. However, hydroelectricity, which is cleaner than coal-CCS or nuclear with respect to climate and health, is an excellent load balancer. As such, hydroelectricity is recommended ahead of the other Tier-3 power sources, particularly for use in combination with intermittent renewables (wind, solar, wave). The Tier-4 technologies are not only the lowest in terms of ranking, but provide no proven climate or mortality benefit and require significant land and water.

The rankings in Table 4 are not significantly sensitive to moderate variations in the weightings. For example, increasing the weighting of mortality by 3% and decreasing that of CO_2e emissions by 3% does not change any overall ranking. Similarly, increasing the weighting of normal operating reliability by 3% and decreasing that of water supply by 3% does not change any ranking. Larger changes in weightings do not change the rankings at the top or bottom. They can result in some shifting in the middle, but not significantly.

14. Example Large-Scale Application

Table 4 suggests that the use of wind-BEVs would result in the greatest benefits among options examined. How many wind turbines, though, are necessary for the large-scale deployment of wind-BEVs? Assuming an RE Power 5 MW turbine (126 m diameter rotor)[116], the U.S. in 2007 would need about 73,000-144,000 5 MW turbines (with a 126-m diameter rotor) to power all onroad (light and heavy-duty) vehicles converted to BEVs (Figure 9, Appendix). The low estimate corresponds to a mean annual wind speed of 8.5 m/s, a BEV plug-to-wheel efficiency of 86%[117], and conversion/transmission/array losses of 10%; the high number, to a mean wind speed of 7.0 m/s, a BEV efficiency of 75%, and losses of 15%. This number of turbines is much less than the 300,000 airplanes the U.S. manufactured during World War II and less than the 150,000 smaller turbines currently installed worldwide. This would reduce U.S. CO_2 by 32.5-32.7% and nearly eliminate 15,000/yr vehicle-related air pollution deaths in 2020. A major reason the number of turbines required is small is that the plug-to-wheel efficiency of BEVs (75-86%) is much greater than the average tank-to-wheel efficiency of fossil-fuel vehicles (17%) (Appendix). As such, a conversion to BEVs reduces the energy required, resulting in a small number of devices. Figure 9 also indicates that the U.S. could theoretically replace 100% of its 2007 carbon-emitting pollution with 389,000-645,000 5 MW wind turbines. Globally, wind could theoretically replace all fossil-fuel carbon with about 2.2-3.6 million 5 MW turbines (assuming the use of new vehicle technologies, such as BEVs) (Appendix).

Figure 9. Thousands of 5 MW wind turbines needed, placed in locations where the mean annual wind speed is 7.0 m/s (high number) to 8.5 m/s (low number), to displace 100% of U.S. CO_2 from each source. Onroad vehicles include light and heavy-duty vehicles and are assumed to be replaced by BEVs. See Appendix for calculations. The corresponding sources of the 5970 MT-CO_2 emitted in the U.S. in 2007 are onroad vehicles: 24.6%, coal electricity: 32.8%, oil electricity: 0.91%, natural gas electricity: 6.1%, and other: 35.7%.



15. Summary

This paper evaluated nine electric power sources (solar-PV, CSP, wind, geothermal, hydroelectric, wave, tidal, nuclear, and coal with CCS) and two liquid fuel options (corn-E85, cellulosic E85) in combination with three vehicle technologies (BEVs, HFCVs, and E85 vehicles) with respect to their effects on global-warming-relevant emissions, air pollution mortality, and several other factors. Twelve combinations of energy source-vehicle type were considered. Among these, the highest-ranked (Tier 1 technologies) were wind-BEVs and wind-HFCVs. Tier 2 technologies were CSP-BEVs, Geo-BEVs, PV-BEVs, tidal-BEVs, and wave-BEVs. Tier 3 technologies were hydro-BEVs, nuclear-BEVs, and CCS-BEVs. Tier 4 technologies were corn- and cellulosic-E85.

Wind-BEVs performed best in seven out of 11 categories, including mortality, climate-relevant emissions, footprint, water consumption, effects on wildlife, thermal pollution, and water chemical pollution. The footprint area of wind-BEVs is 5.5-6 orders of magnitude less than that for E85 regardless of ethanol's source, 4 orders of magnitude less than those of CSP-BEVs or PV-BEVs, 3 orders of magnitude less than those of nuclear- or coal-BEVs, and 2-2.5 orders of magnitude less than those of geothermal, tidal, or wave BEVs.

The intermittency of wind, solar, and wave power can be reduced in several ways: (1) interconnecting geographically-disperse intermittent sources through the transmission system, (2) combining different intermittent sources (wind, solar, hydro, geothermal, tidal, and wave) to smooth out loads, using hydro to provide peaking and load balancing, (3) using smart meters to provide electric power to electric vehicles at optimal times, (4) storing wind energy in hydrogen, batteries, pumped hydroelectric power, compressed air, or a thermal storage medium, and (5) forecasting weather to improve grid planning.

Although HFCVs are less efficient than BEVs, wind-HFCVs still provide a greater benefit than any other vehicle technology aside from wind-BEVs. Wind-HFCVs are also the most reliable combination due to the low downtime of wind turbines, the distributed nature of turbines, and the ability of wind's energy to be stored in hydrogen over time.

The Tier 2 combinations all provide outstanding benefits with respect to climate and mortality. Among Tier 2 combinations, CSP-BEVs result in the lowest CO_2e emissions and mortality. Geothermal-BEVs require the lowest array spacing among all options. Although PV-BEVs result in slightly less climate benefit than CSP-BEVs, the resource for PVs is the largest among all technologies considered. Further, much of it can be implemented unobtrusively on rooftops. Underwater tidal powering BEVs is the least likely to be disrupted by terrorism or severe weather.

The Tier 3 technologies are less beneficial than the others. However, hydroelectricity is an excellent load-balancer and cleaner than coal-CCS or nuclear with respect to CO_2e and air pollution. As such, hydroelectricity is recommended ahead of these other Tier-3 power sources.

The Tier-4 technologies (cellulosic- and corn-E85) are not only the lowest in terms of ranking, but may worsen climate and air pollution problems. They also require significant land relative to other technologies Cellulosic-E85 may have a larger land footprint and higher upstream air pollution emissions than corn-E85. Mainly for this reason, it scored lower overall than corn-E85. Whereas cellulosic-E85 may cause the greatest average human mortality among all technologies, nuclear-BEVs cause the greatest upper-estimate risk of mortality due to the risk of nuclear attacks resulting from the spread of nuclear energy facilities that allows for the production of nuclear weapons. The largest consumer of water is corn-E85. The smallest consumers are wind-BEVs, tidal-BEVs, and wave-BEVs.

In sum, the use of wind, CSP, geothermal, tidal, solar, wave, and hydroelectric to provide electricity for BEVs and HFCVs result in the most benefit and least impact among the options considered. Coal-CCS and nuclear provide less benefit with greater negative impacts. The biofuel options provide no certain benefit and result in significant negative impacts. Because sufficient clean natural resources (e.g., wind, sunlight, hot water, ocean energy, gravitational energy) exists to power all energy for the world, the results here suggest that the diversion of attention to the less efficient or non-efficient options represents an opportunity cost that delays solutions to climate and air pollution health problems.

The relative ranking of each electricity-BEV option also applies to the electricity source when used to provide electricity for general purposes. The implementation of the recommended electricity options for providing vehicle and building electricity requires organization. Ideally, good locations of energy resources would be sited in advance and developed simultaneously with an interconnected transmission system. This requires cooperation at multiple levels of government.

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Appendix

Derivation of results used for this study.

Energy required for vehicles		Low case	High case
A1(S1)	2007 onroad vehicle miles traveled in the U.S. (mi/yr)	3.237E+12	3.237E+12
A2 (S2)	Total onroad vehicle fleet mileage (mpg)	1.711E+01	1.711E+01
A3=A1/A2	Gallons of fuel (gas+diesel) used (gal/yr)	1.892E+11	1.892E+11
A4	Lower heating value gasoline (MJ/kg)	4.400E+01	4.400E+01
A5	Gasoline density (kg/m3)	7.500E+02	7.500E+02
A6	Gallons per cubic meter (gal/m3)	2.642E+02	2.642E+02
A7=A4*A5/A6	Energy stored in gasoline (MJ/gal)	1.249E+02	1.249E+02
A8=A3*A7	Energy needed to power gasoline vehicles (MJ/yr)	2.363E+13	2.363E+13
A9 (S2)	Gasoline vehicle efficiency (fraction)	1.600E-01	1.800E-01
A10=A8*A9	Net energy to power U.S. onroad vehicles (MJ/yr)	3.781E+12	4.254E+12
A11	MJ per kWh	3.600E+00	3.600E+00
A12=A10/A11	Net energy to power U.S. onroad vehicles (kWh/yr)	1.050E+12	1.182E+12
U.S. and world CO2 emissions			
B1 (S3)	U.S. onroad vehicle CO2 2007 (MT-CO2/yr)	1.466E+03	1.466E+03
B2 (S3)	U.S. other-vehicle CO2 (MT-CO2/yr)	4.696E+02	4.696E+02
B3 (S4)	U.S. coal-electricity CO2 2007 (MT-CO2/yr)	1.958E+03	1.958E+03
B4 (S4)	U.S. natural gas-electricity CO2 (MT-CO2/yr)	3.618E+02	3.618E+02
B5 (S4)	U.S. oil electricity CO2 (MT-CO2/yr)	5.450E+01	5.450E+01
B5 (S4)	U.S. non-elect, non-transport. CO2 (MT-CO2/yr)	1.661E+03	1.661E+03
B6=B1+B2+B3+B4+B5	U.S. total fossil CO2 2007 (MT-CO2/yr)	5.971E+03	5.971E+03
B7 (S5)	World total CO2 2007 (MT-CO2/yr)	3.345E+04	3.345E+04
B8 (S6)	Fraction of upstream+combust onroad CO2 from combust	7.500E-01	7.500E-01
B9=B1/B8	U.S. onroad combust+fuel prod CO2 2007 (MT-CO2/yr)	1.955E+03	1.955E+03
U.S. CO2 emissions per kWh electricity generated			
C1 (S7)	US electricity CO2 (g-CO2e/kWH) (1998-2000 avg)	6.060E+02	6.060E+02
C2 (S7)	US electricity CH4 (g-CO2e/kWH) w/GWP 25	1.259E-01	1.259E-01
C3 (S7)	US electricity N2O (g-CO2e/kWH) GWP 298	2.595E+00	2.595E+00
C4=C1+C2+C3	Total US electricity CO2e (g-CO2e/kWh) (1998-2000)	6.087E+02	6.087E+02
Wind turbine characteristics			
D1(S8)	Mean annual wind speed (m/s)	8.500E+00	7.000E+00
D2 (S9)	Turbine rated power (kW)	5.000E+03	5.000E+03
D3 (S9)	Turbine rotor diameter (m)	1.260E+02	1.260E+02
D4=(0.087*D1-D2/D3^2) (S10)	Turbine capacity factor	4.246E-01	2.941E-01
D5	Hours per year (hrs)	8.760E+03	8.760E+03
D6=D2*D4*D5	Turbine energy output without losses (kWh/yr)	1.860E+07	1.288E+07
D7	Turbine effic. with transmission,conversion, array losses	9.000E-01	8.500E-01
D8=D6*D7	Turbine energy output with losses (kWh/yr)	1.674E+07	1.095E+07
D9=(4*D3)*(7*D3)/10^6 (S10)	Area for one turbine accounting for spacing (km2)	4.445E-01	4.445E-01
D10	Diameter of turbine tubular tower (m)	4.000E+00	5.000E+00
D11=PI*(D10/2)^2/10^6	Area of turbine tower touching ground (km^2)	1.257E-05	1.963E-05
D12	Lifetime of wind turbine (yr)	3.000E+01	3.000E+01
D13 (S11)	Energy to manufacture one turbine (kWh/MW)	4.277E+05	1.141E+06

D14=D13*D2/(D12*1000)	Energy to manufacture one turbine (kWh/yr)	7.128E+04	1.901E+05
D15=0.5*(D6a+D6b)	Avg turbine energy output before transmission (kWh/yr)	1.574E+07	1.574E+07
D16=D3*D2/D15	Energy payback time (yr) for given turbine and winds	1.359E-01	3.624E-01
D17=D14*C4	Single-turbine CO2 emissions (g-CO2e/yr)	4.339E+07	1.157E+08
D18=D17/D15	Single-turbine CO2 emissions (g-CO2e/kWh)	2.757E+00	7.352E+00
D19	Time lag (yr) between planning and operation	2.000E+00	5.000E+00
D20	Time (yr) to refurbish after first lifetime	1.000E+00	2.000E+00
D21=C4*(D19+D20*(100yr/ D12))/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	3.247E+01	7.102E+01
D22=D21-D21	Wind minus wind time lag CO2 (g-CO2e/kWh)	0.000E+00	0.000E+00
Wind-powered battery-electric vehicles (wind-BEV)			
E1 (S12)	Battery effic. (delivered to input electricity ratio)	8.600E-01	7.500E-01
E2=A12/E1	Energy required for batteries for U.S. BEV (kWh/yr)	1.221E+12	1.576E+12
E3=E2/D8	Number of turbines required for U.S. wind-BEV	7.298E+04	1.439E+05
E4=E3*D9	Area to separate turbines for U.S. wind-BEV (km^2)	3.244E+04	6.397E+04
E5	Square km per square mile	2.590E+00	2.590E+00
E6	Land area of U.S. (50 states) (mi^2)	3.537E+06	3.537E+06
E7=E6*E5	Land area of U.S. (50 states) (km^2)	9.162E+06	9.162E+06
E8=E4/E7	Fraction of U.S. land turbine spacing for wind-BEV	3.541E-03	6.983E-03
E9	Land area of California (mi^2)	1.560E+05	1.560E+05
E10=E9*E5	Land area of California (km^2)	4.039E+05	4.039E+05
E11=E4/E10	California land fraction for spacing for U.S. wind-BEV	8.031E-02	1.584E-01
E12=E3*D11/E5	Footprint on ground U.S. wind-BEV (km^2)	9.170E-01	2.826E+00
E13=E12/E7	Fraction of U.S. land for footprint for all wind-BEV	1.001E-07	3.084E-07
E14=E3*D17/10^12	Wind-BEV onroad vehicles CO2(MT-CO2e/yr)	3.167E+00	1.665E+01
E15=(B9-E14)/B9	Percent reduction FFOV CO2 due to wind-BEV	9.984E+01	9.915E+01
E16=E15*B9/B6	Percent reduction US CO2 due to wind-BEV	3.268E+01	3.245E+01
E17 (S19)	Water for turbine manufacture (gal-H2O/kWh)	1.000E-03	1.000E-03
E18=E17*D6*E3	Gal-H2O/yr required to run U.S. wind-BEV	1.357E+09	1.854E+09
Wind-powered hydrogen fuel-cell vehicles (wind-HFCV)			
F1 (S2, S13)	hydrogen fuel cell efficiency (fraction)	5.000E-01	4.600E-01
F2=A10/F1	Energy required for U.S. HFCV (MJ/yr)	7.563E+12	9.248E+12
F3	Lower heating value of hydrogen (MJ/kg-H2)	1.200E+02	1.200E+02
F4=F2/F3	Mass of H2 required for fuel for HFCV (kg-H2/yr)	6.304E+10	7.709E+10
F5 (S2, S13)	Leakage rate hydrogen (fraction)	3.000E-02	3.000E-02
F6=F4/(1-F5)	Mass of H2 required with leakage (kg-H2/yr)	6.499E+10	7.947E+10
F7	Higher heating value of hydrogen (MJ/kg-H2)	1.418E+02	1.418E+02
F8 (S14)	Electrolyzer efficiency	7.380E-01	7.380E-01
F9=F7/(F8*F2)	Electrolyzer energy needed per kg-H2 (kWh/kg-H2)	5.337E+01	5.337E+01
F10 (S15)	Compressor Motor size (kW)	3.000E+01	3.000E+01
F11 (S15)	Electricity use as function of motor size (fraction)	6.500E-01	6.500E-01
F12 (S15)	Capacity of compressor (kg/year)	3.030E+04	3.030E+04
F13=D5*F10*F11/F12	Compressor energy needed per kg-H2 (kWh/kg-H2)	5.639E+00	5.639E+00
F14=F9+F13	Electrolyzer+compressor en req. (kWh/kg-H2)	5.901E+01	5.901E+01
F15=F6*F14	Electrolyzer+compressor Energy for all H2 (kWh/yr)	3.835E+12	4.690E+12
F16=F15/D8	Number of turbines required for wind-HFCV	2.292E+05	4.284E+05
F17=F16*D9	Separation area for turbines for wind-HFCV (km2)	1.019E+05	1.904E+05
F18=F17/E7	Fraction of U.S. land for spacing for wind-HFCV	1.112E-02	2.078E-02
F19=F17/E10	Fraction of California land for spacing for wind-HFCV	2.522E-01	4.714E-01
F20=D11*F16/E5	Turbine ground footprint for wind-HFCV (km^2)	2.880E+00	8.411E+00

F21=F16/E3	Ratio of turbines, wind-HFCV:wind-BEV	3.140E+00	2.977E+00
F22=F16*D17/10^12	Wind-HFCV CO2 from turbine lifecycle (MT-CO2e/yr)	9.944E+00	4.957E+01
F23=(B9-F22)/B9	Percent reduction FFOV CO2 due to wind-HFCV	9.949E+01	9.746E+01
F24=F23*B9/B6	Percent reduction US CO2 due to wind-HFCV	3.257E+01	3.190E+01
F25	H2 Molecular weight (g/mol)	2.01588	2.01588
F26	H2O molecular weight (g/mol)	18.01528	18.01528
F27=F26/F25	Water required for electrolyzer (kg-H2O/kg-H2)	8.936682739	8.936682739
F28	Density of liquid water (kg/m3)	1000	1000
F29=F27*A6/F28	Water required for electrolyzer (gal-H2O/kg-H2)	2.361E+00	2.361E+00
F30=F29*F6	Water required for wind HFCV (gal-H2O/yr)	1.534E+11	1.876E+11
F31=E18*F16/E3	Water for turbine manufacturing (gal-H2O/yr)	4.261E+09	5.517E+09
F32=F30+F31	Total water required (gal-H2O/yr)	1.577E+11	1.931E+11
Solar PV panel characteristics			
G1 (S16)	Sample solar panel rated power (W)	1.600E+02	1.600E+02
G2 (S16)	Mean capacity factor accounting for sunlight, PVs, inverter	2.000E-01	1.000E-01
G3=G1*G2*D5/1000	Single-panel energy output before transmis. loss (kWh/yr)	2.803E+02	1.402E+02
G4	Transmission efficiency	9.500E-01	9.000E-01
G5=G3*G4	Single-panel output w/ transmis. loss (kWh/yr)	2.663E+02	1.261E+02
G6 (S16)	Sample solar panel area (m2) plus walking space	1.888E+00	1.888E+00
G7 (S17)	Lifetime of solar panel (yr)	3.000E+01	3.000E+01
G8 (S17)	Single-panel CO2 emissions (g-CO2e/kWh)	1.900E+01	5.900E+01
G9=G8*G3	Single-panel CO2 emissions (g-CO2e/yr)	5.326E+03	8.269E+03
G10	Time lag (yr) between planning and operation	2.000E+00	5.000E+00
G11	Time (yr) to refurbish after first lifetime	1.000E+00	2.000E+00
G12=C4*(G10+G11*100yr/ G7)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	3.247E+01	7.102E+01
G13=G12-D21	Solar PV minus wind time lag CO2 (g-CO2e/kWh)	0.000E+00	0.000E+00
Solar-PV powered battery-electric vehicles (PV-BEV)			
H1=E2/G5	Number of solar panels required for US PV-BEV	4.586E+09	1.249E+10
H2=H1*G6/10^6	Land+roof (km^2) for solar panels to power US PV-BEV	8.658E+03	2.358E+04
H3 (est.)	Fraction of solar panels on rooftops	3.000E-01	3.000E-01
H4=H2*(1-H3)	Land (km^2) for solar panels to power US PV-BEV	6.060E+03	1.650E+04
H5=H4/E7	Fraction of U.S. land for PV-BEV solar panels	6.615E-04	1.801E-03
H6=H4/E10	Fraction of California land for PV-BEV solar panels	1.500E-02	4.086E-02
H7=H4/E12	Ratio of solar-PV to wind land footprint for BEV	6.608E+03	5.841E+03
H8=H4/E4	Ratio of solar-PV to wind total spacing for BEV	1.868E-01	2.580E-01
H9=H1*(G9+G13)/10^12	PV-BEV CO2 emissions from solar panels (MT-CO2e/yr)	2.443E+01	1.033E+02
H10=100*(B9-H9)/B9	Percent reduction FFOV CO2 due to PV-BEV	9.875E+01	9.472E+01
H11=H109*B9/B6	Percent reduction US CO2 due to PV-BEV	3.232E+01	3.100E+01
H12 (S18,S19)	Water for building/cleaning panels (gal-H2O/kWh)	4.000E-02	4.000E-02
H13=H12*G3*H1	Gal-H2O/yr required to run U.S. PV-BEV	5.142E+10	7.002E+10
Corn Ethanol for E85 vehicles			
I1 (S20)	Efficiency of new E85 vehicles	3.200E-01	2.600E-01
I2=A10/I1	Energy required for new E85 vehicles 2007 (MJ/yr)	1.182E+13	1.636E+13
I3	Lower heating value of ETOH (MJ/kg)	2.680E+01	2.680E+01
I4	Density of ETOH (kg/m3)	7.870E+02	7.870E+02
I5=I3*I4/A6	Energy in ETOH (MJ/gal)	7.984E+01	7.984E+01

I6=I2/(0.2*A7+0.8*I5)	Gallons E85 for onroad vehicles (gal)	1.330E+11	1.841E+11
I7=I6*0.8	Gallons of ETOH in E85 for all U.S. onroad vehicles (gal)	1.064E+11	1.473E+11
I8=I6-I7	Gallons of gasoline in E85 for all U.S. onroad vehicles (gal)	2.660E+10	3.683E+10
I9 (S21)	kg-ETOH per bushel of corn	7.860E+00	7.860E+00
I10 (S21)	Bushels per acre on irrigated + nonirrigated land	1.810E+02	1.400E+02
I11	Square meters per acre	4.047E+03	4.047E+03
I12=I9*A6/I4	Gal-ETOH per bushel of corn	2.638E+00	2.638E+00
I13=I12*I10	Gal-ETOH per acre of dry corn	4.775E+02	3.694E+02
I14=I7/(I13*10^6)	Million acres of corn needed for all vehicles	2.228E+02	3.988E+02
I15=I14*I11	Square km of corn for all vehicles	9.016E+05	1.614E+06
I16=I15/E7	Fraction of U.S. land for corn-E85	9.840E-02	1.762E-01
I17=I15/E10	Fraction of California land for corn-E85	2.232E+00	3.995E+00
I18 (S22)	Total acres of harvested corn in U.S. 2003	7.350E+07	7.350E+07
I19 (S23)	Acres of irrigated corn U.S. 2003	9.750E+06	9.750E+06
I20=I19/I18	Fraction of harvested acres that are irrigated	1.327E-01	1.327E-01
I21 (S23)	Bushels per acre on irrigated land	1.780E+02	1.780E+02
I22=I21*I12	Gal-ETOH per acre of dry corn	4.696E+02	4.696E+02
I23 (S23)	Water required for corn (acre-feet-H2O/acre-land)	1.200E+00	1.200E+00
I24	U.S. gallons per acre-foot	3.259E+05	3.259E+05
I25=I23*I24/I22	Gal-H2O-irrigation/gal-ETOH	8.326E+02	8.326E+02
I26=I25*I20	Irrigated+nonirrigated gal-H2O/gal-ETOH	1.104E+02	1.104E+02
I27 (S24)	Gal-H2O-energy /gal-ETOH	1.100E-01	1.100E-01
I28 (S25)	Gal-H2O-factory/gal-ETOH	4.500E+00	4.500E+00
I29=I26+I27+I28	Total Gal-H2O/gal-ETOH	1.151E+02	1.151E+02
I30=I29*I7	Gal-H2O/yr required for all U.S. onroad vehicles	1.224E+13	1.695E+13
I31 (S26)	Total U.S. water use 2000 (gal/day)	4.080E+11	4.080E+11
I32=I31*365 days/yr	Total U.S. water use 2000 (gal/year)	1.489E+14	1.489E+14
I33=I30/I32	Fraction of U.S. water demand for corn-E85	8.220E-02	1.138E-01
I34=I15/E7	Ratio of corn-E85 to wind-BEV land footprint	9.831E+05	5.711E+05
I35 (S6, S28)	Percent change in FFOV CO2 with 100% corn-E85	-2.400E+00	9.300E+01
I36=I35*B9/B6	Percent change in US CO2 with 100% corn-E85	-7.856E-01	3.044E+01
I37=I36*0.30	Percent change in US CO2 with 30% corn-E85	-2.357E-01	9.133E+00
Cellulosic ethanol for E85 (cel-E85) vehicles			
J1 (S27, S29)	Tons dry matter/acre	1.000E+01	2.300E+00
J2 (S27)	Gallons-ETOH/ton-dry matter	1.000E+02	8.000E+01
J3=J1*J2	Gallons-ETOH/acre	1.000E+03	1.840E+02
J4=I7/(J3*10^6)	Million acres of switchgrass for all vehicles	1.064E+02	8.006E+02
J5=J4*I11	Square km of switchgrass for all cel-E85	4.305E+05	3.240E+06
J6=J5/E7	Fraction of U.S. land for cel-E85	4.699E-02	3.536E-01
J7=J5/E10	Fraction of California land for cel-E85	1.066E+00	8.021E+00
J8=J5/E12	Ratio of cel-E85 to wind-BEV land footprint	4.695E+05	1.147E+06
J9=J5/E4	Ratio of cel-E85 to wind-BEV total spacing	1.327E+01	5.064E+01
J10=0.5*I26	Irrigated+nonirrigated gal-H2O/gal-ETOH	5.522E+01	5.522E+01
J11=J10+I27+I28	Total Gal-H2O/gal-ETOH	5.983E+01	5.983E+01
J12=J11*I7	Gal-H2O/yr required for U.S. cel-E85	6.366E+12	8.814E+12
J13=J12/I32	Fraction of U.S. water demand for cel-E85	4.275E-02	5.919E-02
J14 (S6,S28)	Percent change FFOV CO2 with 100% cel-E85	-5.000E+01	5.000E+01
J15=J14*B9/B6	Percent change in US CO2 with 100% cel-E85	-1.637E+01	1.637E+01
J16=J15*0.30	Percent change in US CO2 with 30% cel-E85	-4.910E+00	+4.910E+00

Nuclear-powered battery-electric vehicles (nuclear-BEV)			
K1 (S30)	Average nuclear power plant size (MW)	8.470E+02	8.470E+02
K2 (S31)	Capacity factor globally 2005	8.590E-01	8.590E-01
K3=K1*K2*1000*D5	Energy per plant before transmission (kWh/yr)	6.374E+09	6.374E+09
K4=G4	Transmission efficiency	9.500E-01	9.000E-01
K5=K3*K4	Energy per plant after transmission (kWh/yr)	6.055E+09	5.736E+09
K6=E2/K5	Number nuclear plants to run U.S. nuclear-BEV	2.017E+02	2.747E+02
K7 (S32)	Nuclear CO2 lifecycle emissions (g-CO2e/kWh)	9.000E+00	7.000E+01
K8 (S33)	H2O evaporation nuclear (gal/kWh)	4.000E-01	7.200E-01
K9=K8*K3*K6	Gal-H2O/yr required to run U.S. nuclear-BEVs	5.142E+11	1.260E+12
K10=K9/I30	Fraction of U.S. water demand for nuclear-BEV	3.453E-03	8.464E-03
K11=K10*F16/E3	Fraction of U.S. water demand for nuclear-HFCV	1.084E-02	2.519E-02
K12 (S34)	Land required for mining uranium (ha-year/GWh)	6.000E-02	6.000E-02
K13 (S34)	Footprint+buffer for nuclear facility (ha-year/GWh)	2.600E-01	2.600E-01
K14 (S34)	Land for waste disposal for one plant (km^2)	8.000E-02	8.000E-02
K15	km^2 per hectare	1.000E-02	1.000E-02
K16=(K12+K13)*K15*K3/10^6+K14	Land (km^2) for one nuclear facility with buffer	2.048E+01	2.048E+01
K17 (S35)	Land (km^2) for nuclear facility buildings only	1.000E+00	4.000E+00
K18=K12*K3*K15/10^6+K14+K17	Footprint on ground (km^2) for one facility	4.904E+00	7.904E+00
K19=K16*K6	Land with buffer (km^2) to run US nuclear BEV	4.130E+03	5.624E+03
K20=K18*K6	Footprint on ground (km^2) to run US nuclear-BEV	9.892E+02	2.171E+03
K21=K19/E7	Fraction of US land for nuclear-BEV	4.508E-04	6.138E-04
K22=K21/E7	Fraction of US land for footprint of nuclear-BEV	1.080E-04	2.370E-04
K23=K20/E12	Ratio of nuclear to wind land footprint for BEV	1.079E+03	7.683E+02
K24=K19/E4	Ratio of nuclear to wind total spacing for BEV	1.273E-01	8.791E-02
K25	Lifetime of nuclear power plant (yr)	4.000E+01	4.000E+01
K26 (see text)	Time lag (yr) between planning and operation	1.000E+01	1.900E+01
K27	Time (yr) to refurbish after first lifetime	2.000E+00	4.000E+00
K28=C4*(K26+K27*100yr/K25)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	9.131E+01	1.765E+02
K29=K28-D21	Nuclear minus wind time lag CO2 (g-CO2e/kWh)	5.884E+01	1.055E+02
K30 (see text)	Nuclear emissions from war/terrorism (g-CO2e/kWh)	0.000E+00	4.100E+00
K31=(K7+K28+K30)*E2/10^12	Nuclear-BEV CO2 emissions (MT-CO2e/yr)	8.286E+01	2.830E+02
K32=100*(B9-K31)/B9	Percent reduction FFOV CO2 due to nuclear-BEVs.	9.576E+01	8.552E+01
K33=K32*B9/B6	Percent reduction US CO2 due to nuclear-BEVs	3.135E+01	2.799E+01
Hydroelectric powered battery-electric vehicles (hydro-BEV)			
L1 (S34)	Selected plant size (MW)	1.296E+03	1.296E+03
L2 (S36)	Capacity factor	4.240E-01	4.240E-01
L3=L1*L2*1000*D5	Energy per plant before transmission (kWh/yr)	4.814E+09	4.814E+09
L4=L3*G4	Energy per plant after transmission (kWh/yr)	4.573E+09	4.332E+09
L5=E2/L4	Number of hydro plants to run U.S. hydro-BEV	2.671E+02	3.637E+02
L6 (S34, S37)	Hydro CO2 emissions (g-CO2e/kWh)	1.700E+01	2.160E+01
L7 (S38, see text)	H2O evaporation hydroelectric (gal/kWh)	4.500E+00	7.560E+00
L8=L8*L3*L6	Gal-H2O/yr required to run U.S. BEVs	5.785E+12	1.323E+13
L9=L8/I31	Fraction of U.S. water demand for hydro-BEV	3.885E-02	8.887E-02
L10=L3*F15/E2	Fraction of U.S. water demand for hydro-HFCV	1.220E-01	2.645E-01
L11 (S34)	Area(km^2) required for single reservoir	6.531E+02	6.531E+02

L12=L11*L5	Area (km^2) required to run U.S. BEVs	1.744E+05	2.375E+05
L13=L12/E7	Fraction of US land for hydro-BEV	1.904E-02	2.592E-02
L14=L12/E12	Ratio of hydro to wind land footprint for BEV	1.902E+05	8.405E+04
L15=L12/E4	Ratio of hydro to wind total spacing for BEV	5.377E+00	3.713E+00
L16 (see text)	Lifetime of hydro power plant (yr)	8.000E+01	8.000E+01
L17 (see text)	Time lag (yr) between planning and operation	8.000E+00	1.600E+01
L18	Time (yr) to refurbish after first lifetime	2.000E+00	3.000E+00
L19=C4*(L17+L18*100yr/L16)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	6.392E+01	1.202E+02
L20=L19-D21	Hydro minus wind time lag CO2 (g-CO2e/kWh)	3.145E+01	4.920E+01
L21=(L6+L20)*E2/10^12	Hydro-BEV CO2 emissions (MT-CO2e/yr)	5.917E+01	1.116E+02
L22=100*(B9-L21)/B9	Percent reduction FFOV CO2 due to hydro-BEVs (%)	9.697E+01	9.429E+01
L23=L22*B9/B6	Percent reduction US CO2 due to hydro-BEVs (%)	3.174E+01	3.087E+01
Concentrated solar power powered battery electric vehicles (CSP-BEV) without storage			
M1	Typical plant size (MW)	1.000E+02	1.000E+02
M2 (S39)	Capacity factor without storage	2.500E-01	1.300E-01
M3=M1*M2*1000*D5	Energy per plant before transmission (kWh/yr)	2.190E+08	1.139E+08
M4=G4	Transmission efficiency	9.500E-01	9.000E-01
M5=M3*M4	Energy per plant after transmission (kWh/yr)	2.081E+08	1.025E+08
M6=E2/M5	Number CSP plants to run U.S. CSP-BEV	5.870E+03	1.537E+04
M7 (S40)	Lifetime of CSP plant (yr)	3.000E+01	3.000E+01
M8 (S40, S41)	Energy payback time (yr)	4.167E-01	5.583E-01
M9=0.5*(M3a+M3b)	Avg energy per plant before transmission (kWh/yr)	1.752E+08	1.664E+08
M10=M9*M8/M7	Energy to manufacture one CSP plant (kWh/yr)	2.433E+06	3.098E+06
M11=M10*C4	Single-CSP plant CO2 emissions (g-CO2e/yr)	1.148E+09	1.886E+09
M12=M11/M9	Single-CSP plant CO2 emissions (g-CO2e/kWh)	8.454E+00	1.133E+01
M13 (S42)	H2O consumption wet-cool parabolic trough (gal/kWh)	7.770E-01	7.770E-01
M14=M13*M3*M6	Gal-H2O/yr required to run U.S. CSP-BEV	9.989E+11	1.360E+12
M15=M14/I32	Fraction of U.S. water demand for wet-cool CSP BEV	6.708E-03	9.134E-03
M16=M14*F15/E2	Fraction of U.S. water demand for wet-cool CSP HFCV	2.106E-02	2.719E-02
M17 (S42)	Land area required (km^2) per installed MW CSP	1.900E-02	2.430E-02
M18=M17*M1	Land area required (km^2) for one 100 MW plant	1.900E+00	2.430E+00
M19=M18*M6	Land area (km^2) required to run U.S. CSP-BEV	1.115E+04	3.735E+04
M20=M19/E7	Fraction of U.S. land for CSP-BEV	1.217E-03	4.077E-03
M21=M19/E10	Fraction of California land for CSP-BEV	2.761E-02	9.248E-02
M22=M19/E12	Ratio of CSP to wind footprint area for BEV	1.216E+04	1.322E+04
M23=M19/E4	Ratio of CSP to wind spacing area for BEV	3.438E-01	5.839E-01
M24 (see text)	Time lag (yr) between planning and operation	2.000E+00	5.000E+00
M25	Time (yr) to refurbish after first lifetime	1.000E+00	2.000E+00
M26=C4*(M24+M25*100yr/M7)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	3.247E+01	7.102E+01
M27=M26-D20	CSP minus wind time lag CO2 (g-CO2e/kWh)	0.000E+00	0.000E+00
M28=(M12+M27)*E2/10^{12}	CSP-BEV CO2 emissions (MT-CO2e/yr)	1.033E+01	1.785E+01
M29=100*(B9-M28)/B9	Percent reduction FFOV CO2 due to CSP-BEVs (%)	9.947E+01	9.909E+01
M30=M29*B9/B6	Percent reduction US CO2 due to CSP-BEVs (%)	3.256E+01	3.243E+01
Coal with CCS powering battery-electric vehicles (CCS-BEV)			
N1 (S34)	Typical plant size (MW)	4.250E+02	4.250E+02
N2 (S34, S43)	Capacity factor	8.500E-01	6.500E-01

N3=N1*N2*1000*D5	Energy per plant before transmission (kWh/yr)	3.165E+09	2.420E+09
N4 (S41)	Increase in energy required for CCS (fraction)	1.400E-01	4.000E-01
N5=N3/(1+N4)	Energy available for transmission (kWh/yr)	2.776E+09	1.729E+09
N6=N5*M4	Energy per plant after transmission (kWh/yr)	2.637E+09	1.556E+09
N7=E2/N6	Number of coal plants to run U.S. CCS-BEV	4.631E+02	1.013E+03
N8 (S44)	Coal CO2 direct emissions w/o CCS (g-CO2/kWh)	7.900E+02	1.017E+03
N9 (S43)	CCS CO2 reduction efficiency	9.000E-01	8.500E-01
N10=N8*(1-N9)	Coal CO2 direct emissions w/ CCS (g-CO2/kWh)	7.900E+01	1.526E+02
N11(S44)	Coal non-direct lifecycle CO2 (g-CO2e/kWh)	1.760E+02	2.890E+02
N12=N10+N11	Total lifecycle coal-CCS CO2 (g-CO2e/kWh)	2.550E+02	4.416E+02
N13 (S45)	H2O consumption from coal-fired power (gal/kWh)	4.900E-01	4.900E-01
N14=N13*N3*N7	Gal-H2O/yr required to run U.S. CCS-BEV	7.181E+11	1.201E+12
N15=N14/I32	Fraction of U.S. water demand for CCS-BEV	4.822E-03	8.064E-03
N16 (S34)	Land area for coal facility (km^2)	1.290E+00	1.290E+00
N17 (S34)	Land area for rail to transport coal (km^2)	8.600E-02	8.600E-02
N18 (S34)	Land area for coal mining (km^2)	3.800E+00	3.800E+00
N19=N16+N17+N18	Total land area for one coal plant (km^2)	5.176E+00	5.176E+00
N20=N19*N7	Land area (km^2) to run U.S. CCS-BEV	2.397E+03	5.242E+03
N21=N20/E7	Fraction of U.S. land for CCS-BEV	2.616E-04	5.722E-04
N22=N20/E12	Ratio of CCS to wind footprint area for BEV	2.614E+03	1.855E+03
N23=N20/E4	Ratio of CCS to wind spacing area for BEV	7.390E-02	8.194E-02
N24	Lifetime of coal-CCS power plant (yr)	3.500E+01	3.000E+01
N25 (see text)	Time lag (yr) between planning and operation	8.000E+00	1.600E+01
N26	Time (yr) to refurbish after first lifetime	2.000E+00	3.000E+00
N27=C4*(N25+N26*100yr/N24)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	8.348E+01	1.583E+02
N28=N27-D21	Coal-CCS minus wind time lag CO2 (g-CO2e/kWh)	5.102E+01	8.725E+01
N29=N8-N10	CO2 injection rate into ground (g-CO2/kWh)	7.110E+02	8.645E+02
N30 (see text)	E-folding lifetime against leakage	1.000E+05	5.000E+03
N31=N29-N29*N30*(1-exp(-500yr/N30))/500yr	Average leakage over 500 years (g-CO2/kWh)	1.775E+00	4.182E+01
N32=(N11+N28+N31)*E2/10^12	CCS-BEV CO2 emissions (MT-CO2e/yr)	3.759E+02	8.990E+02
N33=100*(B9-N32)/B9	Percent reduction FFOV CO2 due to CCS-BEVs	8.077E+01	5.400E+01
N34=N33*B9/B6	Percent reduction US CO2 due to CCS-BEVs	2.644E+01	1.768E+01
Geothermal-powered battery-electric vehicles (geo-BEV)			
O1	Typical plant size (MW)	1.000E+02	1.000E+02
O2 (S46)	Capacity factor	9.700E-01	8.900E-01
O3=O1*O2*1000*D5	Energy per plant before transmission (kWh/yr)	8.497E+08	7.796E+08
O4=O3*G4	Energy per plant after transmission (kWh/yr)	8.072E+08	7.017E+08
O5=E2/M4	Number of geothermal plants to run U.S. geo-BEV	1.513E+03	2.245E+03
O6 (S46, S47)	Geothermal lifecycle CO2 (g-CO2e/kWh)	1.510E+01	5.500E+01
O7 (S46)	H2O consumption from geothermal (gal/kWh)	5.000E-03	5.000E-03
O8=O7*O3*O5	Gal-H2O/yr required to run U.S. geo-BEV	6.428E+09	8.753E+09
O9=O8/I32	Fraction of U.S. water demand for geo-BEV	4.316E-05	5.878E-05
O10 (S46)	Geothermal land requirement (m^2/GWh)	4.040E+02	4.040E+02
O11=O10*O3	Land area (km^2) for one plant	3.433E-01	3.150E-01
O12=O11*O5	Land area (km^2) to run U.S. geo-BEV	5.194E+02	7.072E+02
O13=O12/E7	Fraction of U.S. land for geo-BEV	5.669E-05	7.719E-05
O14=O12/E12	Ratio of geothermal to wind footprint area for BEV	5.664E+02	2.503E+02

O15=O12/E4	Ratio of geothermal to wind spacing area for BEV	1.601E-02	1.106E-02
O16	Lifetime of geothermal power plant (yr)	4.000E+01	3.000E+01
O17 (see text)	Time lag (yr) between planning and operation	3.000E+00	6.000E+00
O18	Time (yr) to refurbish after first lifetime	1.000E+00	2.000E+00
O19=C4*(O17+O18*100yr/O16)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	3.348E+01	7.710E+01
O20=O19-D21	Geothermal minus wind time lag CO2 (g-CO2e/kWh)	1.015E+00	6.087E+00
O21=(O6+O20)*E2/10^12	Geo-BEV CO2 emissions (MT-CO2e/yr)	1.968E+01	9.624E+01
O22=100*(B9-O21)/B9	Percent reduction FFOV CO2 due to geo-BEVs	9.899E+01	9.508E+01
O23=O22*B9/B6	Percent reduction US CO2 due to geo-BEVs	3.240E+01	3.112E+01
Wave-powered battery-electric vehicles (wave-BEV)			
P1 (S48)	Device size (MW)	7.500E-01	7.500E-01
P2 (S48)	Nominal wave power (kW/m)	5.500E+01	5.500E+01
P3 (S48)	Nominal energy per device before transmis. (kWh/yr)	2.700E+06	2.700E+06
P4 (S49)	Actual wave power (kW/m)	3.400E+01	2.800E+01
P5=(P7/P2)*P3/(P1*D5*1000)	Capacity factor	2.540E-01	2.092E-01
P6=P1*P5*1000*D5	Energy per device before transmission (kWh/yr)	1.669E+06	1.375E+06
P7=P6*G4	Energy per device after transmission (kWh/yr)	1.586E+06	1.237E+06
P8=E2/P7	Number of wave devices to run U.S. wave-BEV	7.703E+05	1.274E+06
P9 (S50)	Wave CO2 emissions (g-CO2e/kWh)	2.170E+01	2.170E+01
P10 (S48)	Width of wave device (m)	3.500E+00	3.500E+00
P11 (S48)	Length of wave device (m)	1.500E+02	1.500E+02
P12=P10*P11/10^6	Ocean surface footprint (km^2) for one wave device	5.250E-04	5.250E-04
P13=P12*P8	Ocean surface footprint (km^2) to run U.S. wave-BEV	4.044E+02	6.686E+02
P14 (S48)	Ocean surface array spacing (km^2) for one wave device	2.500E-02	2.500E-02
P15=P14*P8	Ocean surface array spacing (km^2) to run U.S. wave-BEV	1.926E+04	3.184E+04
P16=P15/E7	Fraction of U.S. land (over the ocean) for wave-BEV	2.102E-03	3.475E-03
P17=P13/E12	Ratio of wave to wind footprint area for BEV	4.410E+02	2.366E+02
P18=P15/E4	Ratio of wave to wind spacing area for BEV	5.936E-01	4.977E-01
P19 (S50)	Lifetime of wave device (yr)	1.500E+01	1.500E+01
P20 (see text)	Time lag (yr) between planning and operation	2.000E+00	5.000E+00
P21	Time (yr) to refurbish after first lifetime	1.000E+00	2.000E+00
P22=C4*(P20+P21*100yr/P19)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	5.276E+01	1.116E+02
P23=P22-D20	Wave minus wind time lag CO2 (g-CO2e/kWh)	2.029E+01	4.058E+01
P24=(P9+P23)*E2/10^12	Wave-BEV CO2 emissions (MT-CO2e/yr)	5.129E+01	9.813E+01
P25=100*(B9-P24)/B9	Percent reduction FFOV CO2 due to wave-BEVs	9.738E+01	9.498E+01
P26=P25*B9/B6	Percent reduction US CO2 due to wave-BEVs	3.187E+01	3.109E+01
P27 (S19)	Water for device manufacture (gal-H2O/kWh)	1.000E-03	1.000E-03
P28=P27*P6*P8	Gal-H2O/yr required to run U.S. wave-BEV	1.286E+09	1.751E+09
Tidal-powered battery-electric vehicles (tidal-BEV)			
Q1 (S51)	Tidal turbine rated power (MW)	1.000E+00	1.000E+00
Q2 (S52)	Capacity factor	3.500E-01	2.000E-01
Q3=Q1*Q2*1000*D5	Energy per device before transmission (kWh/yr)	3.066E+06	1.752E+06
Q4=Q3*G4	Energy per device after transmission (kWh/yr)	2.913E+06	1.577E+06
Q5=E2/Q4	Number of tidal devices to run U.S. tidal-BEV	4.193E+05	9.992E+05
Q6 (S37)	Tidal CO2 emissions (g-CO2e/kWh)	1.400E+01	1.400E+01
Q7 (S51)	Turbine rotor diameter (m)	1.150E+01	1.150E+01

Q8 (S51)	Ocean floor footprint (km^2) for one tidal device	2.880E-04	2.880E-04
Q9=Q8*Q5	Ocean floor footprint (km^2) to run U.S. tidal-BEV	1.208E+02	2.878E+02
Q10=(4*Q7)*(7*Q7)/10^6 (S10)	Ocean floor array spacing (km^2) for one tidal device	3.703E-03	3.703E-03
Q11=Q10*Q5	Ocean floor array spacing (km^2) to run U.S. tidal-BEV	1.553E+03	3.700E+03
Q12=Q11/E7	Fraction of U.S. land (over ocean floor) for tidal-BEV	1.695E-04	4.038E-04
Q13=Q9/E12	Ratio of tidal to wind footprint area for BEV	1.317E+02	1.018E+02
Q14=Q11/E4	Ratio of tidal to wind spacing area for BEV	4.786E-02	5.784E-02
Q15 (same as wave)	Lifetime of tidal turbine (yr)	1.500E+01	1.500E+01
Q16 (see text)	Time lag (yr) between planning and operation	2.000E+00	5.000E+00
Q17	Time (yr) to refurbish after first lifetime	1.000E+00	2.000E+00
Q18=C4*(Q16+Q17*100yr/Q15)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	5.276E+01	1.116E+02
Q19=Q18-D21	Tidal minus wind time lag CO2 (g-CO2e/kWh)	2.029E+01	4.058E+01
Q20=(Q6+Q19)*E2/10^12	Tidal-BEV CO2 emissions (MT-CO2e/yr)	4.188E+01	8.599E+01
Q21=100*(B9-Q20)/B9	Percent reduction FFOV CO2 due to tidal-BEVs	9.786E+01	9.560E+01
Q22=Q21*B9/B6	Percent reduction US CO2 due to tidal-BEVs	3.203E+01	3.129E+01
Q23 (S19)	Water for turbine manufacture (gal-H2O/kWh)	1.000E-03	1.000E-03
Q24=Q23*Q3*Q5	Gal-H2O/yr required to run U.S. tidal-BEV	1.286E+09	1.751E+09
U.S. energy consumption			
R1 (S53)	Coal electricity kWh/yr 2007	2.024E+12	2.024E+12
R2 (S53)	Oil electricity kWh/yr 2007	5.364E+10	5.364E+10
R3 (S53)	NatGas electricity kWh/yr 2007	8.815E+11	8.815E+11
R4=E2	WBEV Vehicles kWh/yr 2007	1.221E+12	1.576E+12
R5=(B2+B5)*(R1+R2+R3+R4)/(B6-B2-B5)	Other kWh/yr	2.320E+12	2.517E+12
Number of wind turbines required to displace CO2			
S1=R1/D8	Number of turbines to displace U.S. coal electricity	1.210E+05	1.849E+05
S2=R2/D8	Number of turbines to displace U.S. oil electricity	3.205E+03	4.900E+03
S3=R3/D8	Number of turbines to displace U.S. natgas electricity	5.267E+04	8.052E+04
S4=E3	Number of turbines to power U.S. BEVs	7.298E+04	1.439E+05
S5=R5/D8	Number of turbines to displace other U.S. sources	1.386E+05	2.299E+05
S6=S1+S2+S3+S4+S5	Number of turbines to displace all U.S. CO2	3.884E+05	6.441E+05
S7=B7*S6/B6	Number of turbines to displace world CO2	2.176E+06	3.608E+06

“Ref.” refers to references in the main text.

S1. United States Department of Transportation (2008) www.fhwa.dot.gov/Environment/vmtext.htm

S2. Ref. 18

S3. Onroad-vehicle CO_2 was obtained by multiplying the 1999 rate of 1370 MT-CO_2/yr from Ref. 18 by the ratio of 2007 to 1999 total U.S. petroleum CO_2 emissions from Energy Information Administration (2008) U.S. carbon dioxide emissions from energy sources 2007 flash estimate, www.eia.doe.gov/oiaf/1605/flash/flash.html. Other vehicle CO_2 was obtained by subtracting onroad-vehicle CO_2 and oil-electricity CO_2 (present table) from U.S. petroleum CO_2.

S4. 2007 U.S. coal, natural gas, and oil electricity CO_2 were estimated by scaling 2006 emissions from Energy Information Administration (EIA) (2007) Emissions of greenhouse gases report, www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html by the 2007 to 2006 ratio of total energy-related CO_2 coal, natural gas, and petroleum from Energy Information Administration (2008) U.S. carbon dioxide emissions from energy sources 2007 flash estimate, www.eia.doe.gov/oiaf/1605/flash/flash.html. Non-electricity, non-transportation CO_2 was calculated as the total 2007 CO_2 from the same source minus the electricity and transportation emissions from the present table.

S5. Marland, G., T.A. Boden, and R.J. Andres (2008) http://cdiac.ornl.gov/trends/emis/em_cont.htm. 2004 data extrapolated to 2007 using the slope of the carbon emission change per year.

S6. Ref. 58.

S6. Energy Information Administration (EIA) (2002) Updated state-level greenhouse gas emission coefficients for electricity generation 1998-2000, http://tonto.eia.doe.gov/ftproot/environment/e-supdoc-u.pdf. Global warming potentials of 25 and 298 were applied to methane and nitrous oxide, respectively to obtain CO_2e

S7. Ref. 23.

S9. Ref. 116.

S10. Refs. 11, 33.

S11. Ref. 37.

S12. Ref. 117.

S13. Schultz, M.G., T. Diehl, G.P. Brasseur, and W. Zittel (2003) Air pollution and climate-forcing impacts of a global hydrogen economy, Science, 302, 624-627.

S14. National Renewable Energy Laboratory (NREL) (2004) Technology brief: Analysis of current-day commercial electrolyzers, NREL/FS-560-36705, www.nrel.gov/docs/fy04osti/36705.pdf.

S15. Hydro-pac Inc. (2005) C03-40-70/140LX gas compressor for hydrogen specification sheet, www.hydropac.com/HTML/hydrogen-compressor.html.

S16. Table 1, footnote c.

S17. Refs. 40, 44-46,

S18. Ref. 86

S19. Ref. 85.

S20. The low and high range encompass a 2005 Honda gasoline-electric hybrid vehicle tank-to-wheel efficiency of 30% and are both higher than the 2005 Honda gasoline vehicle tank-to-wheel efficiency of about 22% (Fig. 7 of Ref. 18).

S21. Ref. 56. Also, in 2006, an average of 147.5 bushels of corn per harvested acre were produced in the U.S. (11,800 million bushels produced on 80 million acres).

S22. Ref. 77.

S23. Ref. 80.

S24. King, C.W. and M.E. Webber (2008) The water intensity of the plugged-in automotive economy, Environ. Sci. Technol., 42, 4305-4311.

S25. Ref. 81.

S26. Ref. 87.

S27. Ref. 78.

S28. Ref. 61.

S29. Ref. 79.

S30. European Nuclear Society (2008) Nuclear power plants, worldwide, http://www.euronuclear.org/info/npp-ww.htm.

S31. Ref. 20.

S32. Refs. 16, 49-51.

S33. Ref. 84.

S34. Ref. 31.

S35 American Nuclear Society (2008) http://www2.ans.org/pi/brochures/pdfs/power.pdf

S36 Energy Information Administration (EIA) (2006) Average capacity factors by energy source, www.eia.doe.gov/cneaf/electricity/epa/figes3.html, Table 1.

S37. Ref. 40.

S38. Ref. 83 for high value. The low value is estimated by attributing one-third of reservoir water to hydroelectric power.

S39. Low value from Ref. 16 and Table 1 for California solar; high value from Ref. 22.

S40. Ref. 39.

S41. Ref. 38.

S42. Ref. 86 gives CSP land area requirements 0.0203-0.0243 km^2/MW without storage (and 0.0324-0.047 km^2/MW with storage) (Table 3-1) and water requirements of 2.8 m^3/MWh consumption and 0.14 m^3/MWh for cleaning (Section A.1.3); Abengoa Solar (2008) Concentrated solar power, http://www.solucar.es/sites/solar/en/tec_ccp.jsp gives 0.019 km^2/MW without storage (and 0.038 km^2/MW with storage). Ref. 16 gives 0.02 km^2/MW without storage.

S43. Ref. 32.

S44. Ref. 49.

S45. Ref. 85.

S46. Ref. 27.

S47. Ref. 43.

S48. Pelamis Wave Power (2008) P-750 wave energy converter, http://www.pelamiswave.com/media/pelamisbrochure.pdf.

S49. Kane, M. (2005) California small hydropower and ocean wave energy resources, California Energy Commission, CEC-500-2005-075, www.energy.ca.gov/2005publications/CEC-500-2005-074/CEC-500-2005-074.PDF.

S50. Ref. 41.

S51. Ref. 97.

S52. Ref. 28.

S53. Energy Information Administration (2008) Annual energy outlook 2008, http://www.eia.doe.gov/oiaf/aeo/electricity.html.