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Effects of biofuels vs. other new vehicle technologies on air pollution, global warming, land use and water

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Abstract: The use of biofuels, particularly ethanol, has expanded in the last few years based significantly on the premise that biofuels replacing fossil fuels may reduce global warming and air pollution problems. While this claim is still being debated, the real comparison should be between biofuels and other emerging technologies. It is found here that both corn-E85 (85% ethanol/15% gasoline) and cellulosic-E85 degrade air quality and climate by up to two orders of magnitude more than Battery-Electric Vehicles (BEVs) or Hydrogen Fuel Cell Vehicles (HFCVS) powered by either solar Photovoltaics (PVs), Concentrated Solar Power (CSP), wind, geothermal, hydroelectric, wave, or tidal power. As such, the use of cellulosic or corn ethanol at the expense of the other options will cause certain damage to health, climate, land, and water supply in the future.

Keywords: global warming; air pollution; wind and solar energy; geothermal energy; tidal and wave energy hydroelectric energy; ethanol; battery-electric vehicles; hydrogen fuel cell vehicles.

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1 Introduction

This paper compares the impacts of vehicles using E85 (a blend of 85% ethanol and 15% gasoline) with the impacts of other new vehicle technologies on climate, air quality, land use and water supply. Two types of ethanol are considered: corn and cellulosic (from prairie grass). The alternative vehicles compared include BEV and HFCV where hydrogen is produced by electrolysis. The sources of electricity considered in the electric vehicles are PV, CSP, wind, geothermal, hydroelectric, wave, tidal, nuclear and coal with CCS. Only wind is considered for producing hydrogen for the HFCV, but the ratio of results between the wind-HFCV and wind-BEV cases can be applied to any of the other BEV electric power sources to estimate HFCV results for that source. 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 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 will change significantly over time, particularly as a technology is adopted and used on a large scale. The global availability of each raw energy resource (e.g., sunlight, wind, tides) is discussed in Jacobson (2009) as are other issues related to each technology, including effects on energy security, reliability, effects on wildlife and effects on water pollution. In the following sections, the effects of each vehicle option are examined with respect to climate-relevant emissions, air pollution effects, land use and water supply.

2 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 owing 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 potential emissions from the burning of cities resulting from explosions arising from nuclear-energy-related proliferation of nuclear weapons.

2.1 Lifecycle emissions

Table 1 summarises ranges of the lifecycle CO_2e emission per kWh of electricity generated for the electric power sources considered (all technologies except the biofuels). The sources or derivations of the lifecycle estimates are summarised here and calculated/referenced in the Appendix.

Table 1 Equivalent carbon-dioxide lifecycle, opportunity-cost emissions owing to planning-to-operation delay 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

Table 1 Equivalent carbon-dioxide lifecycle, opportunity-cost emissions owing to planning-to-operation delay 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 (continued)

Technology	*Lifecycle*	*Opportunity cost emissions due to delays*	*War/terrorism (nuclear) or 500-year leakage (CCS)*	*Total*
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

2.1.1 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 m/s to 8.5 m/s. Wind speeds of 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 (Jacobson and Masters, 2001). About 13% of land outside of Antarctica has such wind speeds at 80 m, 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 (Archer and Jacobson, 2005). 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, which encompasses the measured capacity factors, 0.33–0.35, of all wind farms installed in the USA between 2004 and 2007 (Wiser and Bolinger, 2008). As such, this wind-speed range is the relevant range for considering the large-scale deployment of wind. Krohn (1997) analysed the energy required and the energy payback time to manufacture, install, operate and scrap a 600 kW wind turbine. The energy required for these processes was 4.277×10^6 kWh per installed MW. 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 US electrical grid, the resulting emissions from the turbine are 2.8–7.4 g-CO_2e/kWh and the resulting energy payback time is 1.6 months (8.5 m/s) – 4.3 months (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.

2.1.2 CSP

Concentrated Solar Power (CSP) is estimated as the second-lowest emitter of CO_2e. For CSP, we assume the energy payback time of Marchie van Voorthuysen (2006) and Mendax (2008), given as 5–6.7 months and a plant lifetime of 40 years (Mendax, 2008), resulting in an emission rate of 8.5–11.3 g-CO_2e/kWh (Appendix).

2.1.3 Wave and tidal

Few analyses of the lifecycle carbon emissions for wave or tidal power have been performed. For tidal power, we use the value 14 g-CO_2e/kWh (Tahara et al., 1997), determined from a 100 MW tidal turbine farm. The energy payback time was calculated to be 3–5 months. Tahara et al. (1997) also calculate emissions for a 2.5 MW farm as 119 g-CO_2e/kWh, but because we are evaluating large-scale deployment, we consider only the larger farm. For wave power, we use the value 21.7 g-CO_2e/kWh from Banerjee et al. (2006), who also estimate the energy payback time as 1 year for devices that have an estimated lifetime of 15 years.

2.1.4 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 (Tahara et al., 1997; Spitzley and Keoleian, 2005). In addition, some CO_2 and CH_4 emissions from dams can occur owing to microbial decay of dead organic matter under the water of a dam, particularly if the reservoir was not logged before being filled (e.g., Delmas, 2005). Such emissions are generally highest in tropical areas and lowest in northern latitudes.

2.1.5 Geothermal

Geothermal power plant lifecycle emissions include those owing 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 (Meier, 2002) 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 (GEA, 2008).

2.1.6 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 (Pearce and Lau, 2002; Bankier and Gale, 2006; Banerjee et al., 2006). New systems consisting of CdTe, silicon ribbon, multicrystalline silicon and monocrystalline 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 (Fthenakis and Alsema, 2006). 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 Raugei et al. (2007), and Fthenakis and Kim (2007). Since large-scale PV deployment at very high latitudes is unlikely, such latitudes are not considered for this payback analysis.

2.1.7 Nuclear

Nuclear power plant emissions include those owing to uranium mining, enrichment, and transport and waste disposal as well as those owing 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 (WNO, 2008b) and the upper number slightly above the average of 66 g-CO_2e/kWh from Sovacool (2008), who reviewed 103 new and old lifecycle studies of nuclear energy. Koch (2000), Fthenakis and Kim (2007), and IPCC (2007) estimate mean lifecycle emissions of nuclear reactors as 59, 16–55 and 40 g-CO_2e/kWh, respectively; thus, the range appears within reason.

2.1.8 Coal-CCS

Coal-CCS power plant lifecycle emissions include emissions owing 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. Excluding direct emissions, the lifecycle emissions of a coal power plant, including coal mining, transport and plant construction/decommissioning, range from 175 to 290 g-CO_2e/kWh (WNO, 2008b). Without CCS, the direct emissions from coal-fired power plants worldwide are around 790–1020 g-CO_2e/kWh. The carbon dioxide direct emission reduction efficiency owing to CCS is 85–90% (IPCC, 2005). 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 pulverised-coal plant with CCS (Odeh and Cockerill, 2008).

The addition of CCS equipment to a coal power plant results in an additional 14–25% energy required for coal-based Integrated Gasification Combined Cycle (IGCC) systems and 24–40% for supercritical pulverised-coal plants with current technology (IPCC, 2005). Most of the additional energy is needed to compress and purify carbon dioxide. This additional energy increases either the coal required for an individual plant or 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, owing to addition of CCS; however, either the number of plants required increases or the kWh required per plant increases.

2.1.9 Corn and cellulosic ethanol

Several studies have examined the lifecycle emissions of corn and cellulosic ethanol (e.g., Shapouri et al., 2003; Pimentel and Patzek, 2005; Kim and Dale, 2005; Farrell et al., 2006; Patzek, 2006; Hammerschlagr, 2006; DeLucchi, 2006; Tilman et al., 2006; Fargione et al., 2008; Searchinger et al., 2008). These studies generally accounted for the emissions owing to planting, cultivating, fertilising, watering, harvesting and transporting crops, the emissions owing to producing ethanol in a factory and transporting it, and emissions owing to running vehicles, although with differing assumptions in most cases. Only one of these studies, DeLucchi (2006), accounted for the emissions of soot, the second-leading component of global warming (Jacobson, 2000, 2001, 2004a), cooling aerosol particles, nitric oxide gas, carbon monoxide gas, or detailed treatment of the nitrogen cycle. DeLucchi (2006) is also the only study to account for the accumulation of CO_2 in the atmosphere owing to the time lag between biofuel use and regrowth, identified in Jacobson (2004b). Further, DeLucchi (2006), Fargione et al. (2008) and Searchinger et al. (2008) are the only studies to consider substantially the change in carbon storage owing to

- converting natural land or cropland to fuel crops
- 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
- 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.

Searchinger et al. (2008) performed such a calculation in the most detail, determining the effect of price changes on land-use change with spatially distributed global data for land conversion between non-cropland and cropland and an econometric model.

Searchinger et al. (2008) 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 (2006), 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 US CO_2e by about 52.5% compared with light-duty gasoline in the USA. We use results from these two studies to bind 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 USA.

2.2 Carbon emissions owing 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 more likely become cleaner; thus, the "opportunity-cost emissions" will probably go down 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 US 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 two years and the time between the construction permit approval and issue is about 0.5 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, US nuclear plant construction times increased from around seven years in 1971 to 12 years in 1980 (Cohen, 1990). The median construction time for reactors in the USA built since 1970 is nine years (Koomey and Hultman, 2007). US 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 (Koomey and Hultman, 2007) 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 (WNO, 2008a) and those times based on historic data (Koomey and Hultman, 2007), we assume future construction times owing to nuclear power plants as 4–9 years. Thus, the overall time between planning and operation of a nuclear power plant ranges from 10 to 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 to 5 years, with more typical times from 1 to 3 years. The construction period for a small to medium wind farm (15 MW or less) is one year and for a large farm is 1–2 years (van de Wekken, 2008). 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 two years (GEA, 2008). We use a range of 1–3 years. Construction times for a cluster of geothermal plants of 250 MW or more are at least two years (Chandrasekharam, 2008). 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 four years (1931–1935). Shasta Dam required seven years (1938–1945). Glen Canyon Dam required 10 years (1956–1966). Gardiner Dam required eight years (1959–1967). Construction on Three Gorges Dam in China began on 14 December 1994 and is expected to be fully operated 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 down time 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 owing to the total down time for each technology over 100 years of operation assuming that emissions during down time 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 owing to planning-to-operation time, so any thing 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 down time of an ethanol refinery is unlikely to increase CO_2e emissions relative to current transportation emissions.

Results of this analysis are summarised in Table 1. For solar-PV, CSP and wind, the opportunity cost was zero since these all had the lowest CO_2e emissions owing to delays. Wave and tidal had an opportunity cost only because the lifetimes of these technologies are shorter than those of the other technologies owing 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.

2.3 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 the existing fractured rock/overly porous soil or through new fractures in rock or soil resulting from an earthquake. Here, a range in potential emissions owing 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 (2005) summarises 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 owing 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, 2005, p.216), the e-folding lifetime against leakage is approximately $\tau = 100{,}000$ years. We use this as our high estimate of lifetime and $\tau = 5000$ years as the low estimate, which corresponds to 18% leakage over 1000 years, closer to that of some observed methane leakage. 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 (IPCC, 2005), and no initial CO_2 in the geological formation, the CO_2 emission 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 owing to CO_2 leakage. We use the average leakage rate over 500 years as a relevant time period for considering leakage.

2.4 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 programmes, the risk of a limited nuclear exchange between countries or the detonation of a nuclear device by terrorists has increased owing 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 owing 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) (Toon et al., 2007). Worldwide, nine countries have known nuclear weapons stockpiles (USA, Russia, UK, France, China, India, Pakistan, Israel and 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 programme, either to produce highly enriched uranium or to separate plutonium, and facilities in 13 countries are active (Toon et al., 2007, Table 2). 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 (Toon et al., 2007). Currently, about 30,000 nuclear warheads exist worldwide, with 95% in the USA and Russia, but enough refined and unrefined material to produce another 100,000 weapons (NAS, 2005).

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 (Toon et al., 2007). The soot emissions would cause significant short- and medium-term regional cooling (Robock et al., 2007). Despite short-term cooling, the CO_2 emissions would cause long-term warming, as they do with biomass burning (e.g., Jacobson, 2004b). 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%; tyres and other rubbers, 59–91%; synthetic fibres, 63–86% (USEPA, 2003); woody biomass, 41–45%; charcoal, 71% (Andreae and Merlet, 2001); 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 owing to nuclear energy in 2005 was 2768 TWh/yr. If one nuclear exchange as described earlier occurs over the next 30 years, the net carbon emissions owing 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 0–4.1 g-CO_2/kWh. This emission rate is placed in context in Table 1.

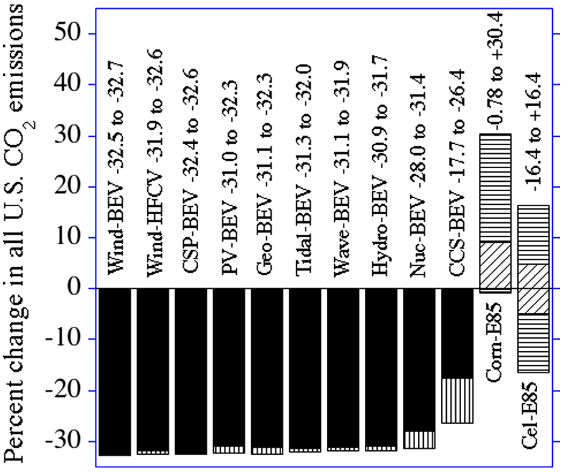
2.5 *Analysis of CO_2e owing to converting vehicles to BEVs, HFCVs, or E85 vehicles*

Here, we estimate the comparative changes in CO_2e emissions owing to each of the 11 technologies considered when they are used to power all (small and large) onroad vehicles in the USA 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 that hydrogen is produced by electrolysis, with the electricity derived from wind power. Other methods of producing hydrogen are not analysed 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 have the advantage that the fuelling time is shorter than the charging time for electric vehicle (generally 1–30 h, 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 USA 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 USA CO_2 (not CO_2e) emissions owing to any vehicle-powering technology. The upstream CO_2 emissions are about 94.3% of the upstream CO_2e emissions (DeLucchi, 2006).

Figure 1 compares calculated percent changes in total emitted US CO_2 emissions owing to each energy options considered here when onroad vehicles are converted to BEVs or HFCVs (in the case of the electric power sources) or E85 vehicles (in the case of corn or cellulosic ethanol). It is also assumed that all CO_2e increases or decreases that are due to the technology have been converted to CO_2 for purposes of comparing with US CO_2 emissions. Owing to land-use constraints, it is unlikely that corn or cellulosic ethanol could power more than 30% of US onroad vehicles, so the figure also shows CO_2 changes owing to 30% penetrations of E85. The other technologies, aside from hydroelectric power (limited by land as well), could theoretically power the entire US onroad vehicle fleet so are not subject to the 30% limit.

Figure 1 Percent changes in actual US 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. 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 (see online version for colours)



Source: Jacobson (2009)

Converting to corn-E85 could cause either no change in or increase in 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 US carbon by 32.5–32.7% since wind turbines are 99.2–99.8% carbon free over a 30-year lifetime. Using HFCVs, where hydrogen is produced by wind electrolysis, could reduce US 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%. Using nuclear to power BEVs may reduce US carbon by a lesser amount, 28.0–31.4%, due primarily to opportunity-cost emissions arising from planning and construction delays. Of the electric power sources, coal-CCS producing vehicles result in the least emission reduction owing to the lifecycle carbon of coal-CCS together with leakage and long construction times.

3 Effects on air pollution emissions and mortality

Although climate change is a significant driver for motivating 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 owing to energy generation or use.

Here, we examine the effects of the energy technologies considered on air-pollution-relevant emissions and resulting mortality. For wind, solar-PV, CSP, tidal, wave and hydroelectric power, air-pollution-relevant emissions arise only owing to the construction, installation, maintenance and decommissioning of the technology and as a result of planning-to-operation delays. 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 owing 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% of those of a coal-fired power plant.

For coal-CCS, emissions also arise owing to coal combustion since the CCS equipment itself generally does not reduce pollutants aside from CO_2. For example, with CCS equipment, 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 increased fuel use by 15.7%, SO_x emissions by 17.9% and NO_x emissions by 11% (IPCC, 2005). In another case, CCS equipment in a pulverised-coal plant increased fuel use by 31.3%, increased NO_x emissions by 31%, and increased NH_3 emissions by 22% but the addition of another control device decreased SO_x emissions by 99.7% (IPCC, 2005).

For nuclear power, pollutant emissions also include emissions owing to the mining and transport of uranium. It is also necessary to take into the account the potential fatalities owing to nuclear war or terrorism caused by the proliferation of nuclear energy facilities worldwide.

To evaluate the technologies, we estimate the change in the US premature death rate owing 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 US vehicle fleet (Jacobson et al., 2005; Colella et al., 2005) as do BEVs, the deaths owing 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 that lifecycle emissions of the vehicles themselves are similar for all vehicles so do not evaluate those emissions. We estimate deaths owing to each electricity-generating technology as one minus the percent reduction in total CO_2e emissions owing to the technology (Table 1) 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 USA from model calculations similar to those in Jacobson (2008). Thus, the deaths owing to all BEV and HFCV options are attributed only to the electricity generation plant itself (as no pollution emanates from these vehicles). Because the number of deaths in most cases 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 vapour changes on air pollution (Jacobson, 2008), using it as a surrogate may be reasonable.

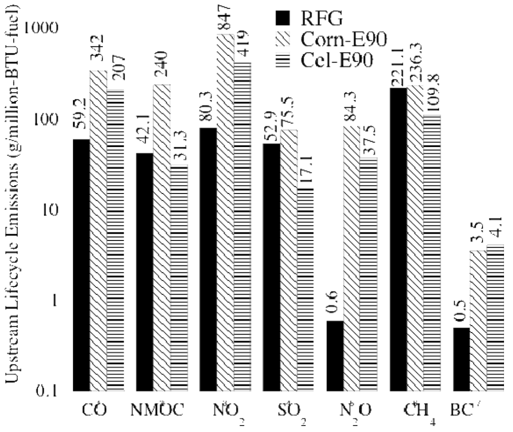
For nuclear energy, we add, in the high case, the potential death rate owing to a nuclear exchange, as described in Section 4.4, which could kill up to 16.7 million people. Dividing this number by 30 years and the ratio of the USA to world population today (302 million/6.602 billion) gives an upper limit to deaths scaled to US population of 25,500/year attributable to nuclear energy. We do not add deaths to the low estimate, since we assume that the low probability of a nuclear exchange is zero.

The 2020 premature death rates owing to corn- and cellulosic-E85 are calculated by considering the 2020 death rate from light- and heavy-duty gasoline onroad vehicles, the change in the death rate owing to changes in upstream emissions between gasoline and E85, and the change in the death rate owing to changes in the exhaust/evaporative emissions between gasoline and E85.

Changes in deaths owing to the upstream emissions from E85 production were determined as follows. Figure 2 shows the upstream lifecycle emissions for multiple gases and black carbon from reformulated gasoline (RFG), corn-E90 and cellulosic-E90, obtained from DeLucchi (2006). The upstream cycle accounts for fuel dispensing, fuel distribution and storage, fuel production, feedstock transmission, feedstock recovery, land-use changes, cultivation, fertiliser manufacture, gas leaks and flares and emissions displaced. The figure indicates that the upstream cycle emissions of CO, NO_2, N_2O and BC are 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 (2001) gives a very rough estimate of the health-weighed upstream emission changes of E90 vs. 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 4.5) gives death rate increases of 5.0% and 7.5% for corn- and cellulosic-E90, respectively, relative to RFG.

The changes in onroad deaths were taken from Jacobson (2007), who found that a complete penetration of E85-fuelled vehicles (whether from cellulose or corn) might increase the air pollution premature death rate in the USA by anywhere from 0 to 180 people per year in 2020 over gasoline vehicles.

Figure 2 Upstream lifecycle emissions of several individual pollutants from corn-E90 and cellulosic-E90 relative to Reformulated Gasoline (RFG)



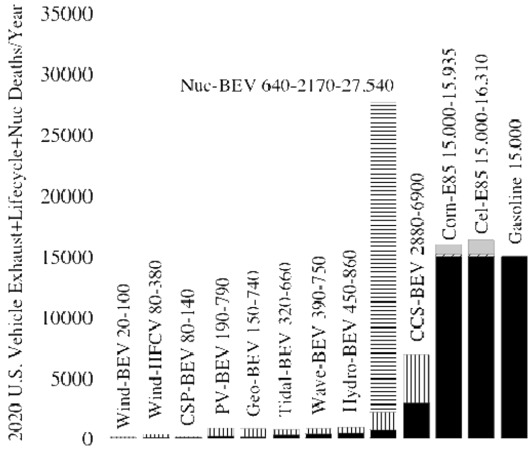
Source: Jacobson (2009)

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 (2002) 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 owing to undernutrition does not require starvation. When food prices increase, poor people eat less and, without necessarily starving, subject themselves to a higher chance of dying owing to undernutrition and resulting susceptibility to disease. Here, we do not quantify the effects of corn-E85 or cellulosic-E85 on mortality owing to the lack of a numerical estimate of the relationship between food prices and undernutrition mortality but note that it is probably occurring.

Figure 3 indicates that E85 may increase premature deaths compared with gasoline, due primarily to upstream changes in emissions but also owing to changes in onroad vehicle emissions. Cellulosic ethanol may increase overall deaths, which is more than that caused by corn ethanol, although this result rests heavily on the precise particulate matter emissions of corn- vs. cellulosic-E85. Because of 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 3 also indicates that each E85 vehicle will 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 owing 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 is estimated to 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 owing to E85 does not affect the conclusions of this study.

Figure 3 Estimates of future (c. 2020) US 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 US population, owing 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 US death rate owing to upstream emissions from producing and distributing E85 minus those from producing and distributing gasoline (see text) and the slanted lines are the additional death rate from tailpipe emissions as calculated for the USA in Jacobson (2007).

Source: Jacobson (2009)

Further, coal-CCS is 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 of the electric power sources with respect to lifecycle and opportunity-cost emissions. The least damaging technologies are wind-BEV followed by CSP-BEV, then wind-HFCV.

4 Land and ocean use

In this section, the land, ocean surface, or ocean floor required by the different technologies are 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 owing 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 minimise interference by other turbines in an array is $A = 4D \times 7D$, where D is the rotor diameter (m) (Masters, 2004). This equation predicts that for a 5-MW turbine with a 126 m diameter rotor, about 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 2D 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 1D rather than 2D. 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.

4.1 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 owing to transmission lines. Transmission lines within a wind farm are always underground. Those between the wind farm and the public utility electricity distribution system are usually underground. 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 new electric power sources although this assumption may result in a small error in footprint size.

4.2 Tidal

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.

4.3 Wave

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 (owing 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.

4.4 Nuclear

In the case of nuclear power, a buffer zone is needed around each plant for safety. In the USA, 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 minimise security risks. The land required for nuclear power also includes that for uranium mining and disposal of nuclear waste. Spitzley and Keoleian (2005) estimate the lands required for uranium mining and nuclear facility with a buffer zone as 0.06 ha-yr/GWh and 0.26 ha-yr/GWh, respectively, and that for waste for a single sample facility as about 0.08 km^2. For the average plant worldwide, this translates to 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.

4.5 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), whereas those 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.

4.6 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.

4.7 Footprint and spacing for onroad vehicles

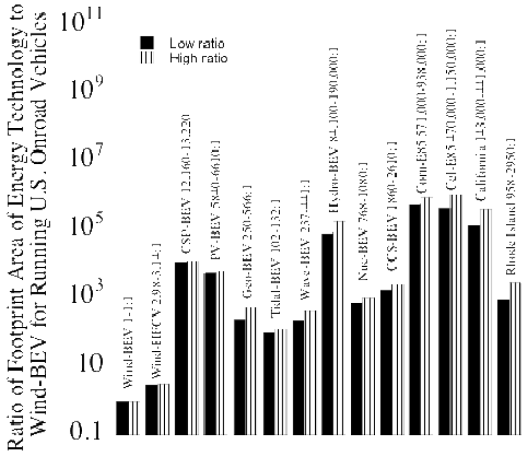
Here, we compare the footprint and spacing areas required for each technology to power all onroad (small and large) vehicles in the USA. All numbers are derived in the Appendix. Wind-BEVs require by far the least footprint on the ground over land or ocean (1–2.5 km^2). Tidal-BEVs would not take any ocean 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 US 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 USA before corn use for biofuels of around 75 million (USDA, 2008). Cellulosic ethanol could require either less or more land than corn ethanol, depending on the yield of cellulosic material for acre. Hladik (2006) estimates 5–10 tons of dry matter per acre. However, Schmer et al. (2008) provided data from established switchgrass fields of 2.32–4.95 tons/acre. 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 US onroad vehicles with E85.

Figure 4 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, four orders of magnitude less than those of CSP- or PV-BEVs, three 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 three times that for wind-BEVs owing 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) only if 80% or more (rather than the 30% assumed) of all future PV is put on rooftops.

Figure 5 compares the fractional area of the USA (50 states) required for spacing (footprint plus separation area for wind, tidal, wave, nuclear; footprint for the others) needed by each technology. The array spacing requirements of wind-BEVs are about 0.35–0.7% of all US 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 US 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 US 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 US land. Solar-PV powering US BEVs requires 0.077–0.18% of US land for spacing (and footprint), or 19–26% of the spacing area required for wind-BEVs.

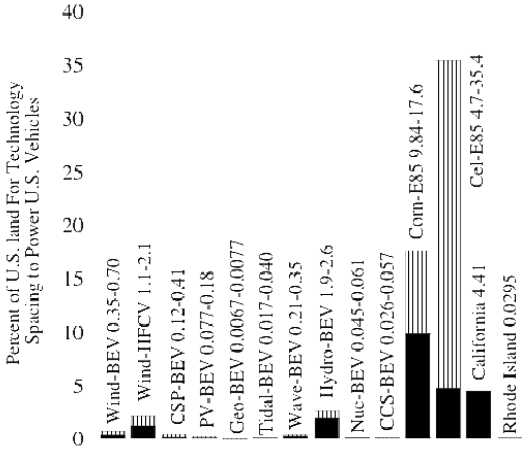
Similarly, CSP-BEVs need about 0.12–0.41% of US land or 34–59% of the spacing required for wind-BEV.

Figure 4 Ratio of the footprint area on land or water required to power all vehicles in the USA 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



Source: Jacobson (2009)

Figure 5 Low (solid) and high (solid + lines) fractions of US land area (50 states) required for the spacing (footprint plus separation area for wind, tidal, wave, and nuclear; footprint only for the others) of each energy technology for powering all US vehicles in 2007. Also shown are the fractions of US land occupied by California and Rhode Island. Multiply fractions by the area of the USA (9,162,000 km^2) to obtain area required for technology



Source: Jacobson (2009)

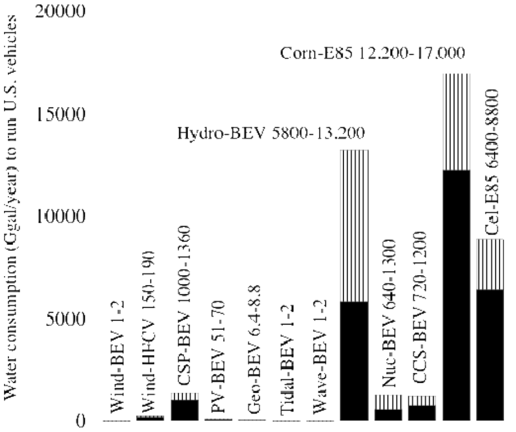
A 100 MW geothermal plant requires a land area of about 0.33 km^2. This translates to about 0.006–0.008% of US land for running all US BEVs, or about 1.1–1.6% the array spacing required for wind-BEVs. Powering all onroad vehicles in the USA with nuclear power would require about 0.045–0.061% of US land for spacing, or about 9–13% that of wind-BEVs. The land required for CCS-BEVs is 0.03–0.06% of the USA, 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 US 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 US onroad vehicle fleet with corn-E85 requires 9.8–17.6% of all 50 US states, or 2.2–4.0 States of California. Cellulosic-E85 would require from 4.7–35.4% of US 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 US land. 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 one-third that of wind-BEVs.

5 Water supply

Water shortages are an important issue in many parts of the world and may become more so as surface 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 US vehicles. Results are summarised in Figure 6 and derived in the Appendix.

Figure 6 Low (solid) and high (solid + line) estimates of water consumption (Gigagallons/year) required to replace all US 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 US water consumption in 2000 was 148,900 Ggal/year



Source: Jacobson (2009)

5.1 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 USA was irrigated. With 1.2 acre-feet of irrigation water per acre of land applied to corn (USDA, 2003), an average of 178 bushels per acre (USDA, 2003), 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 non-irrigated) corn. In Minnesota ethanol factories, about 4.5 L of water were required to produce one litre of 100% ethanol in 2005 (IATP, 2006). Much of the water consumed is by evaporation during cooling and wastewater discharge. Thus, the irrigation plus ethanol-factory water requirement for corn ethanol in the USA is about 107 gal-H_2O/gal-ethanol, on average. This compares with an estimate by Pimentel (2003) of 159 gal-H_2O/gal-ethanol, who used statistics for an earlier year with a higher fraction of irrigated corn.

5.2 Cellulosic-E85

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 USA in 2003, whereas irrigated + non-irrigated corn produced 139.7 bushels per harvested acre (USDA, 2008), it is more 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).

5.3 Hydroelectric

Hydroelectric power consumes water as a result of evaporation from the surface of reservoirs. However, 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. Further, in the absence of the reservoir, most of the water would not be available for water supply and would be lost to the ocean or to evaporation from rivers and streams. 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 (Torcellini et al., 2003). 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 all the purposes described earlier. As such, their fraction attributable to hydroelectricity should be less than or equal to their capacity factor (25–42%) since this gives the fraction of their turbines' possible electrical output actually used. The main reason that capacity factors are not near 100% is generally because the water in the dam is conserved for use at different times during the year for the other purposes listed. We thus estimate the water consumption rate as 4.5–7.6 gal/kWh.

5.4 Nuclear

Nuclear power plants, usually located near large bodies of surface water, require more water than other fossil-fuel power plants (EPRI, 2002) 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 its source, but some of the water is lost by evaporation. The water consumption (from evaporation) in a nuclear power plant ranges from 0.4 to 0.72 gal/kWh, depending on the type of cooling technology used (EPRI, 2002).

5.5 Coal-CCS

Carbon capture and sequestration projects result in water consumption owing to the coal plant, estimated as 0.49 gal/kWh (AWEA, 2008). The increased electricity demand owing 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.

5.6 CSP

Concentrated Solar Power (CSP) 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 is 0.74 gal-H_2O/kWh for water cooling and 0.037 gal-H_2O/kWh for mirror cleaning (Stoddard et al., 2006). The water consumption for central-tower receiver CSP cooling and cleaning is 0.74 gal-H_2O/kWh (Stoddard et al., 2006). If air cooling is used, water use decreases significantly, but efficiency also decreases. For parabolic dish-shaped reflectors, only water for cleaning is needed.

5.7 Geothermal, wind, wave, tidal, solar-PV

Geothermal plants consume some water during their construction and operation. GEA (2008) estimates the consumption as 0.005 gal/kWh. Wind turbines, wave devices and tidal turbines do not consume water, except in the manufacture of the devices. AWEA (2008) estimates such water consumption owing to wind as 0.001 gal-H_2O/kWh. 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 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.

5.8 Comparison of water consumption

Figure 6 compares the water consumed by each technology when used to power all US 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 US onroad vehicles were converted to corn-E85, an additional 8.2–11.4% of the total water consumed for all purposes in the USA 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 6.

6 Additional effects

The technologies discussed affect wildlife through their effect on land-use conversion (which is proportional to footprint), their physical interaction with wildlife and air/water chemical releases. Each technology also has a different level of reliability for regular use and in extreme weather and a different risk of being a target of a terrorist attack. These issues are discussed, and combined with the other effects discussed here to provide an overall ranking of the benefits or disbenefits of each technology in Jacobson (2009).

7 Summary

This paper compared the effects on climate, air quality, land use and water supply of the large-scale use of corn- and cellulosic-E85 vehicles with the use of BEVs and HFCVs powered by alternative source of electricity. The electric power sources considered were PV, CSP, wind, geothermal, hydroelectric, wave, tidal, nuclear and coal with CCS. Both corn-E85 and cellulosic-E85 were concluded to degrade air quality, climate, land and water supply significantly relative to the alternative options examined. In fact, both corn- and cellulosic-E85 were found to degrade air quality and climate by up to two orders of magnitude more than BEVs or HFCVs powered by solar PV, concentrated solar, wind, geothermal, hydroelectric, wave, or tidal power. The air pollution impacts of cellulosic-E85 were found to be greater than those of corn-E85 due primarily to the upstream emission increase in the former over the latter. The land required for cellulosic-E85 may also exceed that of corn-E85 and the land required for both will exceed that required for the footprint on the ground of wind powering BEVs by a factor of 500,000 to 1 million. Because corn- and cellulosic-E85 degrade air quality and may or may not worsen climate problems relative to fossil fuels while other technologies improve both and use less land and water, the use of cellulosic or corn ethanol at the expense of the other options will cause certain damage to human health, climate, land and water supply relative to these other technologies.

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References

Abengoa Solar (2008) *Concentrated Solar Power*, http://www.solucar.es/sites/solar/en/tec_ccp.jsp

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

American Wind Energy Association (AWEA) (2008) http://www.awea.org/faq/water.html

Andreae, M.O. and Merlet, P. (2001) 'Emission of trace gases and aerosols from biomass burning', *Global Biogeochemical Cycles*, Vol. 15, pp.955–966.

Archer, C.L. and Jacobson, M.Z. (2005) 'Evaluation of global wind power', *J. Geophys. Res.*, Vol. 110, D12110, doi:10.1029/2004JD005462.

Banerjee, S., Duckers, L.J., Blanchard, R. and Choudhury, B.K. (2006) 'Life Cycle analysis of selected solar and wave energy systems', *Advances in Energy Research*, www.ese.iitb.ac.in/aer2006_files/papers/142.pdf

Bankier, C. and Gale, S. (2006) 'Energy payback of roof mounted photovoltaic cells', *Energy Bulletin*, www.energybulletin.net/17219.html

Chandrasekharam, D. (2008) *Geothermal Energy Resources and Utilization*, www.geos.iitb.ac.in/geothermalindia/pubs/geoweb.htm

Cohen, B. (1990) *The Nuclear Energy Option*, Plenum Press, www.phyast.pitt.edu/~blc/book/chapter9.html

Colella, W.G., Jacobson, M.Z. and Golden, D.M. (2005) 'Switching to a US hydrogen fuel cell vehicle fleet: the resultant change in emissions, energy use, and global warming gases', *J. Power Sources*, Vol. 150, pp.150–181.

Delmas, R. (2005) 'Long term greenhouse gas emissions from the hydroelectric reservoir of Petit Saut (French Guiana) and potential impacts', *Global Warming and Hydroelectric Reservoirs*, CDD 363.73874, pp.117–124.

DeLucchi, M. (2006) *Lifecycle Analyses of Biofuels*, www.its.ucdavis.edu/publications/2006/UCD-ITS-RR-06-08.pdf

Eberhard, M. and Tarpenning, M. (2006) *The 21st Century Electric Car*, www.evworld.com/library/Tesla_21centuryEV.pdf

Electric Power Research Institute (EPRI) (2002) 'Water and sustainability (Volume 3): U.S. water consumption for power production – the next half century', *Topical Report 1006786*, March, www.epriweb.com/public/000000000001006786.pdf

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

Energy Information Administration (EIA) (2006) *Average Capacity Factors by Energy Source*, www.eia.doe.gov/cneaf/electricity/epa/figes3.html

Energy Information Administration (EIA) (2007a) *Nuclear Power Plant Operations, 1957–2006*, www.eia.doe.gov/aer/txt/ptb0902.html

Energy Information Administration (EIA) (2007b) *Emissions of Greenhouse Gases Report*, www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html

Energy Information Administration (EIA) (2008a) *U.S. Carbon Dioxide Emissions from Energy Sources 2007 Flash Estimate*, www.eia.doe.gov/oiaf/1605/flash/flash.html

Energy Information Administration (EIA) (2008b) *Annual Energy Outlook 2008*, http://www.eia.doe.gov/oiaf/aeo/electricity.html

European Nuclear Society (2008) *Nuclear Power Plants, Worldwide*, http://www.euronuclear.org/info/npp-ww.htm

Fargione, J., Hill, J., Tilman, D., Polasky, S. and Hawthorne, P. (2008) 'Land clearing and the biofuel carbon debt', *Science*, Vol. 319, pp.1235–1238.

Farrell, A.E., Plevin, R.J., Turner, B.T., Jones, A.D., O'Hare, M. and Kammen, D.M. (2006) 'Ethanol can contribute to energy and environmental goals', *Science*, Vol. 311, pp.506–508.

Fthenakis, V. and Alsema, E. (2006) 'Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004-early 2005 status', *Prog. Photovolt: Res. Appl.*, Vol. 14, pp.275–280.

Fthenakis, V.M. and Kim, H.C. (2007) 'Greenhouse-gas emissions from solar electric- and nuclear power: a life-cycle study', *Energy Policy*, Vol. 35, pp.2549–2557.

Geothermal Energy Association (GEA) (2008) www.geo-energy.org/aboutGE/environment.asp, www.geo-energy.org/aboutGE/basics.asp, www.geo-energy.org/aboutGE/powerPlantCost.asp, www.geo-energy.org/aboutGE/potentialUse.asp#world

Hammerschlagr, R. (2006) 'Ethanol's energy return on investment, a survey of the literature 1990-present', *Environ. Sci. Technol.*, Vol. 40, pp.1744–1750.

Hladik, M. (2006) *Cellulose Ethanol is Ready to go*, www.c2c.ucsb.edu/summit2006/pdf/presentation_maurice_hladik.pdf

Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S. and Maupin, M.A. (2004) 'Estimated use of water in the United States in 2000', *USGS Circular 1268*, http://pubs.usgs.gov/circ/2004/circ1268/

Hydro-pac Inc. (2005) *C03-40-70/140LX Gas Compressor for Hydrogen Specification Sheet*, www.hydropac.com/HTML/hydrogen-compressor.html

Institute for Agriculture and Trade Policy (IATP) (2006) *Water Use by Ethanol Plants: Potential Challenges*, www.agobservatory.org/library.cfm?refid=89449, Summary Data Sheet.

Intergovernmental Panel on Climate Change (IPCC) (2005) IPCC Special Report on Carbon Dioxide Capture and Storage, Prepared by working group III, Metz. B., Davidson, O., de Coninck, H.C., Loos, M. and Meyer, L.A. (Eds.): Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 Pages, http://arch.rivm.nl/env/int/ipcc/

Intergovernmental Panel on Climate Change (IPCC) (2007) *Working Group III*, http://www.mnp.nl/ipcc/pages_media/FAR4docs/final_pdfs_ar4/Chapter04.pdf

International Energy Agency (IEA) (2007) *Key World Energy Statistics 2007*, www.iea.org/textbase/nppdf/free/2007/key_stats_2007.pdf

Jacobson, M.Z. (2000) 'A physically-based treatment of elemental carbon optics: implications for global direct forcing of aerosols', *Geophys. Res. Lett.*, Vol. 27, pp.217–220, www.stanford.edu/group/efmh/jacobson/IVa.html

Jacobson, M.Z. (2001) 'Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols', *Nature*, Vol. 409, pp.695–697, www.stanford.edu/group/efmh/jacobson/IVb.html

Jacobson, M.Z. (2004a) 'The climate response of fossil-fuel and biofuel soot, accounting for soot's feedback to snow and sea ice albedo and emissivity', *J. Geophys. Res.*, Vol. 109, D21201, doi:10.1029/2004JD004945, www.stanford.edu/group/efmh/jacobson/VIIIc.html

Jacobson, M.Z. (2004b) 'The short-term cooling but long-term global warming due to biomass burning', *J. Clim.*, Vol. 17, No. 15, pp.2909–2926.

Jacobson, M.Z. (2007) 'Effects of ethanol (E85) versus gasoline vehicles on cancer and mortality in the United States', *Environ. Sci. Technol.*, Vol. 41, No. 11, pp.4150–4157, doi:10.1021/es062085v, www.stanford.edu/group/efmh/jacobson/E85vWindSol

Jacobson, M.Z. (2008) 'On the causal link between carbon dioxide and air pollution mortality', *Geophysical Research Letters*, Vol. 35, L03809, doi:10.1029/2007GL031101.

Jacobson, M.Z. (2009) 'Review of solutions to global warming, air pollution, and energy security', *Energy and Environmental Science*, Vol. 2, pp.148–173, doi:10.1039/b809990c.

Jacobson, M.Z. and Masters, G.M. (2001) 'Exploiting wind versus coal', *Science*, Vol. 293, pp.1438–1438, www.stanford.edu/group/efmh/jacobson/Ia.html

Jacobson, M.Z., Colella, W.G. and Golden, D.M. (2005) 'Cleaning the air and improving health with hydrogen fuel cell vehicles', *Science*, Vol. 308, pp.1901–1905, www.stanford.edu/group/efmh/jacobson/fuelcellhybrid.html

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

Kim, S. and Dale, B. (2005) 'Environmental aspects of ethanol derived from no-tilled corn grain: nonrenewable energy consumption and greenhouse gas emissions', *Biomass Bioenergy*, Vol. 28, pp.475–489.

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

Koch, F.H. (2000) 'Hydropower-internalized costs and externalized benefits', *International Energy Agency (IEA)-Implementing Agreement for Hydropower Technologies and Programs*, Ottawa, Canada, www.nei.org/keyissues/protectingtheenvironment/lifecycleemissionsanalysis/

Koomey, J. and Hultman, N.E. (2007) 'A reactor-level analysis of busbar costs for US nuclear plants, 1970–2005', *Energy Policy*, Vol. 35, pp.5630–5642.

Krohn, S. (Ed.) (1997) 'The energy balance of modern wind turbines', *Wind Power*, Vol. 16, pp.1–15.

Leitner, A. (2002) *Fuel from the Sky: Solar Power's Potential for Western Energy Supply*, NREL/SR-550-32160, www.nrel.gov/csp/pdfs/32160.pdf

Lunar Energy (2008) http://www.lunarenergy.co.uk/productOverview.htm

Marchie van Voorthuysen, E.H. du (2006) 'Large-scale concentrating solar power (CSP) technology', in Badescu, V., Cathcart, R.B. and Schuiling, R.D. (Eds.): *Macro-Engineering: A Challenge for the Future*, Springer, Chapter 3.

Marland, G., Boden, T.A. and Andres, R.J. (2008) http://cdiac.ornl.gov/trends/emis/em_cont.htm

Masters, G.M. (2004) *Renewable and Efficient Electric Power Systems*, John Wiley and Sons, New York, 654 Pages.

Meier, P.J. (2002) *Life-cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis*, Fusion Technology Institute, U. Wisconsin, UWFDM-1181, http://fti.neep.wisc.edu/pdf/fdm1181.pdf

Mendax (2008) *Solar Power Plants*, Microsystems, http://www.mendax.com/Solution-Warehouse.aspx?slnid=75&iid=

National Academy of Sciences (NAS) (2005) *Monitoring Nuclear Weapons and Nuclear-Explosive Materials*, National Academy of Sciences, Washington DC, 250 Pages.

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

Ocean Energy Council (2008) www.oceanenergycouncil.com/index.php/Tidal-Energy/Tidal-Energy.html

Odeh, N. and Cockerill, T.T. (2008) 'Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage', *Energy Policy*, Vol. 36, pp.367–380.

Patzek, T.W. (2006) *The Real Biofuel Cycle*, http://petroleum.berkeley.edu/patzek/BiofuelQA/Materials/RealFuelCycles-Web.pdf

Pearce, J. and Lau, A. (2002) 'Net energy analysis for sustainable energy production from silicon based solar cells', *Proceedings of Solar 2002, Sunrise on the Reliable Energy Economy*, 15–20 June, Reno, Nevada, http://jupiter.clarion.edu/~jpearce/Papers/netenergy.pdf

Pelamis (2008) *P-750 Wave Energy Converter*, Pelamis Wave Power, http://www.pelamiswave.com/media/pelamisbrochure.pdf

Pimentel, D. (2003) 'Ethanol fuels: energy balance, economics, and environmental impacts are negative', *Natural Resources Research*, Vol. 12, pp.127–134.

Pimentel, D. and Patzek, T.W. (2005) 'Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower', *Nat. Resource Res.*, Vol. 14, pp.67–76.

Raugei, M., Bargigli, S. and Ulgiati, S. (2007) 'Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si', *Energy*, Vol. 32, pp.1310–1318.

RePower Systems (2008) *Repower 5M*, www.repower.de/index.php?id=237&L=1

Robock, A., Oman, L., Stenchikov, G.L., Toon, O.B., Bardeen, C. and Turco, R.P. (2007) 'Climate consequences of regional nuclear conflicts', *Atmos. Chem. Phys.*, Vol. 7, pp.2003–2012.

Schmer, M.R., Vogel, K.P., Mitchell, R.B. and Perrin, R.K. (2008) 'Net energy of cellulosic ethanol from switchgrass', *Proc. Nat. Acad. Sci.*, Vol. 105, pp.464–469.

Schultz, M.G., Diehl, T., Brasseur, G.P. and Zittel, W. (2003) 'Air pollution and climate-forcing impacts of a global hydrogen economy', *Science*, Vol. 302, pp.624–627.

Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D. and Yu, T-H. (2008) 'Use of US cropland for biofuels increases greenhouse gases through emissions from land-use change', *Science*, Vol. 319, pp.1238–1240.

Shapouri, H., Duffield, J.A. and Wang, M. (2003) 'The energy balance of corn ethanol revisited', *Trans. ASAE*, Vol. 46, pp.959–968.

Sovacool, B.K. (2008) 'Valuing the greenhouse gas emissions from nuclear power: a critical survey', *Energy Policy*, Vol. 36, pp.2940–2953.

Spadaro, J.V. and Rabl, A. (2001) 'Damage costs due to automotive air pollution and the influence of street canyons', *Atmos. Environ.*, Vol. 35, pp.4763–4775.

Spitzley, D.V. and Keoleian, G.A. (2005) *Life Cycle Environmental and Economic Assessment of Willow Biomass Electricity: A Comparison with other Renewable and Non-renewable Sources*, Report No. CSS04-05R. http://css.snre.umich.edu/css_doc/CSS04-05R.pdf

Stoddard, L., Abiecunas, J. and O'Connell, R. (2006) 'Economic, energy, and environmental benefits of concentrating solar power in California', *NREL/SR-550-39291*, http://www.nrel.gov/docs/fy06osti/39291.pdf

Tahara, K., Kojimaa, T. and Inaba, A. (1997) 'Evaluation of CO_2 payback time of power plant by LCA', *Energy Conversion and Management*, Vol. 38, Supp. 1, pp.S615–S620, http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V2P-4DS9V40-3K&_user=145269&_rdoc=1&_fmt=&_orig=search&_sort=d&view=c&_acct=C000012078&_version=1&_urlVersion=0&_userid=145269&md5=8381efaf8294dc1d2054d3882d53d667

Tilman, D., Hill, J. and Lehman, C. (2006) 'Carbon-negative biofuels from low-input high-diversity grassland', *Science*, Vol. 314, pp.1598–1600.

Toon, O.B., Turco, R.P., Robock, A., Bardeen, C., Oman, L. and Stenchikov, G.L. (2007) 'Atmospheric effects and societal consequences of regional scale nuclear conflicts and acts of individual nuclear terrorism', *Atmos. Chem. Phys.*, Vol. 7, pp.1973–2002.

Torcellini, P., Long, N. and Judkoff, R. (2003) *Consumptive Water Use for US Power Production*, National Renewable Energy Laboratory, US Department of Energy, www.nrel.gov/docs/fy04osti/33905.pdf

United States Department of Agriculture (USDA) (2003) *Estimated Quantity of Water Applied and Method of Distribution by Selected Crops Harvested: 2003 and 1998*, www.agcensus.usda.gov/Publications/2002/FRIS/tables/fris03_28.pdf

United States Department of Agriculture (USDA) (2008) *Agriculture Baseline Database*, http://www.ers.usda.gov/db/baseline/default.asp?ERSTab=3

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

United States Environmental Protection Agency (USEPA) (2003) *Methodology for Estimating CO_2 Emissions from Municipal Solid Waste Combustion*, http://yosemite.epa.gov/OAR/globalwarming.nsf/UniqueKeyLookup/LHOD5MJT9U/$File/2003-final-inventory_annex_i.pdf

Van de Wekken, T. (2008) *Doing It Right: The Four Seasons of Wind Farm Development*, www.renewableenergyworld.com/rea/news/reworld/story?id=52021

Wiser, R. and Bolinger, M. (2008) *Annual Report on U.S. Wind Power Installation, Cost, and Performance Trends: 2007*, LBNL-275E, US Department of Energy, http://eetd.lbl.gov/ea/ems/reports/lbnl-275e.pdf

World Health Organization (WHO) (2002) *The World Health Report, Annex Table 9*, http://www.who.int/whr/2002/en/whr2002_annex9_10.pdf

World Nuclear Association (WNO) (2008a) *Energy Analysis of Power Systems*, www.world-nuclear.org/info/inf11.html

World Nuclear Association (WNO) (2008b) *Comparative Carbon Dioxide Emissions from Power Generation*, www.world-nuclear.org/education/comparativeco2.html

Appendix

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
A1(S1)	2007 onroad vehicle miles travelled in the USA (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/m^3)	7.500E+02	7.500E+02

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
A6	Gallons per cubic meter (gal/m^3)	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 US 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 US onroad vehicles (kWh/yr)	1.050E+12	1.182E+12
US and World CO_2 emissions			
B1 (S3)	US onroad vehicle CO_2 2007 (MT-CO_2/yr)	1.466E+03	1.466E+03
B2 (S3)	US other-vehicle CO_2 (MT-CO_2/yr)	4.696E+02	4.696E+02
B3 (S4)	US coal-electricity CO_2 2007 (MT-CO_2/yr)	1.958E+03	1.958E+03
B4 (S4)	US natural gas-electricity CO_2 (MT-CO_2/yr)	3.618E+02	3.618E+02
B5 (S4)	US oil electricity CO_2 (MT-CO_2/yr)	5.450E+01	5.450E+01
B5 (S4)	US non-elect, non-transport. CO_2 (MT-CO_2/yr)	1.661E+03	1.661E+03
B6=B1+B2+B3+B4+B5	US total fossil CO_2 2007 (MT-CO_2/yr)	5.971E+03	5.971E+03
B7 (S5)	World total CO_2 2007 (MT-CO_2/yr)	3.345E+04	3.345E+04
B8 (S6)	Fraction of upstream+combust onroad CO_2 from combust	7.500E-01	7.500E-01
B9=B1/B8	US onroad combust+fuel prod CO_2 2007 (MT-CO_2/yr)	1.955E+03	1.955E+03
US CO_2 emissions per kWh electricity generated			
C1 (S7)	US electricity CO_2 (g-CO_2e/kWH) (1998–2000 avg)	6.060E+02	6.060E+02
C2 (S7)	US electricity CH_4 (g-CO_2e/kWH) w/GWP 25	1.259E-01	1.259E-01
C3 (S7)	US electricity N_2O (g-CO_2e/kWH) GWP 298	2.595E+00	2.595E+00
C4=C1+C2+C3	Total US electricity CO_2e (g-CO_2e/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

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
D3 (S9)	Turbine rotor diameter (m)	1.260E+02	1.260E+02
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 (km^2)	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 CO_2 emissions (g-CO_2e/yr)	4.339E+07	1.157E+08
D18=D17/D15	Single-turbine CO_2 emissions (g-CO_2e/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	CO_2 emissions due to time lag (g-CO_2e/kWh)	3.247E+01	7.102E+01
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 US BEV (kWh/yr)	1.221E+12	1.576E+12

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
E3=E2/D8	Number of turbines required for US wind-BEV	7.298E+04	1.439E+05
E4=E3*D9	Area to separate turbines for US 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 US (50 states) (mi^2)	3.537E+06	3.537E+06
E7=E6*E5	Land area of US (50 states) (km^2)	9.162E+06	9.162E+06
E8=E4/E7	Fraction of US 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 US wind-BEV	8.031E-02	1.584E-01
E12=E3*D11/E5	Footprint on ground US wind-BEV (km^2)	9.170E-01	2.826E+00
E13=E12/E7	Fraction of US land for footprint for all wind-BEV	1.001E-07	3.084E-07
E14=E3*D17/10^12	Wind-BEV onroad vehicles CO_2 (MT-CO_2e/yr)	3.167E+00	1.665E+01
E15=(B9-E14)/B9	Percent reduction FFOV CO_2 due to wind-BEV	9.984E+01	9.915E+01
E16=E15*B9/B6	Percent reduction US CO_2 due to wind-BEV	3.268E+01	3.245E+01
E17 (AWEA, 2008)	Water for turbine manufacture (gal-H_2O/kWh)	1.000E-03	1.000E-03
E18=E17*D6*E3	Gal-H_2O/yr required to run US 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 US HFCV (MJ/yr)	7.563E+12	9.248E+12
F3	Lower heating value of hydrogen (MJ/kg-H_2)	1.200E+02	1.200E+02
F4=F2/F3	Mass of H_2 required for fuel for HFCV (kg-H_2/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 H_2 required with leakage (kg-H_2/yr)	6.499E+10	7.947E+10
F7	Higher heating value of hydrogen (MJ/kg-H_2)	1.418E+02	1.418E+02
F8 (S14)	Electrolyser efficiency	7.380E-01	7.380E-01

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
F9=F7/(F8*F2)	Electrolyser energy needed per kg-H_2 (kWh/kg-H_2)	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-H_2 (kWh/kg-H_2)	5.639E+00	5.639E+00
F14=F9+F13	Electrolyser+compressor en req. (kWh/kg-H_2)	5.901E+01	5.901E+01
F15=F6*F14	Electrolyser+compressor Energy for all H_2 (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 (km^2)	1.019E+05	1.904E+05
F18=F17/E7	Fraction of US 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*D16/10^12	Wind-HFCV CO_2 from turbine lifecycle (MT-CO_2e/yr)	9.944E+00	4.957E+01
F23=(B9-F22)/B9	Percent reduction FFOV CO_2 due to wind-HFCV	9.949E+01	9.746E+01
F24=F23*B9/B6	Percent reduction US CO_2 due to wind-HFCV	3.257E+01	3.190E+01
F25	H_2 Molecular weight (g/mol)	2.01588	2.01588
F26	H_2O molecular weight (g/mol)	18.01528	18.01528
F27=F26/F25	Water required for electrolyser (kg-H_2O/kg-H_2)	8.936682739	8.936682739
F28	Density of liquid water (kg/m^3)	1000	1000
F29=F27*A6/F28	Water required for electrolyser (gal-H_2O/kg-H_2)	2.361E+00	2.361E+00
F30=F29*F6	Water required for wind HFCV (gal-H_2O/yr)	1.534E+11	1.876E+11
F31=E18*F16/E3	Water for turbine manufacturing (gal-H_2O/yr)	4.261E+09	5.517E+09
F32=F30+F31	Total water required (gal-H_2O/yr)	1.577E+11	1.931E+11

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
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 (m^2) 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 CO_2 emissions (g-CO_2e/kWh)	1.900E+01	5.900E+01
G9=G8*G3	Single-panel CO_2 emissions (g-CO_2e/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	CO_2 emissions due to time lag (g-CO_2e/kWh)	3.247E+01	7.102E+01
G13=G12-D21	Solar-PV minus wind time lag CO_2 (g-CO_2e/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 US 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 CO_2 emissions from solar panels (MT-CO_2e/yr)	2.443E+01	1.033E+02

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
H10=100*(B9-H9)/B9	Percent reduction FFOV CO_2 due to PV-BEV	9.875E+01	9.472E+01
H11=H109*B9/B6	Percent reduction US CO_2 due to PV-BEV	3.232E+01	3.100E+01
H12 (S18,S19)	Water for building/cleaning panels (gal-H_2O/kWh)	4.000E-02	4.000E-02
H13=H12*G3*H1	Gal-H_2O/yr required to run US 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/m^3)	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 US onroad vehicles (gal)	1.064E+11	1.473E+11
I8=I6-I7	Gallons of gasoline in E85 for all US 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 + non-irrigated 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 US 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 US 2003	7.350E+07	7.350E+07
I19 (S23)	Acres of irrigated corn US 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-H_2O/acre-land)	1.200E+00	1.200E+00
I24	US gallons per acre-foot	3.259E+05	3.259E+05
I25=I23*I24/I22	Gal-H_2O-irrigation/gal-ETOH	8.326E+02	8.326E+02
I26=I25*I20	Irrigated+non-irrigated gal-H_2O/gal-ETOH	1.104E+02	1.104E+02

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
I27 (S24)	Gal-H_2O-energy /gal-ETOH	1.100E-01	1.100E-01
I28 (S25)	Gal-H_2O-factory/gal-ETOH	4.500E+00	4.500E+00
I29=I26+I27+I28	Total Gal-H_2O/gal-ETOH	1.151E+02	1.151E+02
I30=I29*I7	Gal-H_2O/yr required for all US onroad vehicles	1.224E+13	1.695E+13
I31 (S26)	Total US water use 2000 (gal/day)	4.080E+11	4.080E+11
I32=I31*365 days/yr	Total US water use 2000 (gal/year)	1.489E+14	1.489E+14
I33=I30/I32	Fraction of US 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 CO_2 with 100% corn-E85	–2.400E+00	9.300E+01
I36=I35*B9/B6	Percent change in US CO_2 with 100% corn-E85	–7.856E-01	3.044E+01
I37=I36*0.30	Percent change in US CO_2 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 US 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+non-irrigated gal-H_2O/gal-ETOH	5.522E+01	5.522E+01
J11=J10+I27+I28	Total Gal-H_2O/gal-ETOH	5.983E+01	5.983E+01
J12=J11*I7	Gal-H_2O/yr required for US cel-E85	6.366E+12	8.814E+12
J13=J12/I32	Fraction of US water demand for cel-E85	4.275E-02	5.919E-02
J14 (S6,S28)	Percent change FFOV CO_2 with 100% cel-E85	–5.000E+01	5.000E+01
J15=J14*B9/B6	Percent change in US CO_2 with 100% cel-E85	–1.637E+01	1.637E+01
J16=J15*0.30	Percent change in US CO_2 with 30% cel-E85	–4.910E+00	+4.910E+00

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
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 US nuclear-BEV	2.017E+02	2.747E+02
K7 (S32)	Nuclear CO_2 lifecycle emissions (g-CO_2e/kWh)	9.000E+00	7.000E+01
K8 (S33)	H_2O evaporation nuclear (gal/kWh)	4.000E-01	7.200E-01
K9=K8*K3*K6	Gal-H_2O/yr required to run US nuclear-BEVs	5.142E+11	1.260E+12
K10=K9/I30	Fraction of US water demand for nuclear-BEV	3.453E-03	8.464E-03
K11=K10*F16/E3	Fraction of US 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

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
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	CO_2 emissions due to time lag (g-CO_2e/kWh)	9.131E+01	1.765E+02
K29=K28-D21	Nuclear minus wind time lag CO_2 (g-CO_2e/kWh)	5.884E+01	1.055E+02
K30 (see text)	Nuclear emissions from war/terrorism (g-CO_2e/kWh)	0.000E+00	4.100E+00
K31=(K7+K28+K30)*E2/10^12	Nuclear-BEV CO_2 emissions (MT-CO_2e/yr)	8.286E+01	2.830E+02
K32=100*(B9-K31)/B9	Percent reduction FFOV CO_2 due to nuclear-BEVs.	9.576E+01	8.552E+01
K33=K32*B9/B6	Percent reduction US CO_2 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 US hydro-BEV	2.671E+02	3.637E+02
L6 (S34, S37)	Hydro CO_2 emissions (g-CO_2e/kWh)	1.700E+01	2.160E+01
L7 (S38, see text)	H_2O evaporation hydroelectric (gal/kWh)	4.500E+00	7.560E+00
L8=L8*L3*L6	Gal-H_2O/yr required to run US BEVs	5.785E+12	1.323E+13
L9=L8/I31	Fraction of US water demand for hydro-BEV	3.885E-02	8.887E-02
L10=L3*F15/E2	Fraction of US 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 US 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

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
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	CO_2 emissions due to time lag (g-CO_2e/kWh)	6.392E+01	1.202E+02
L20=L19-D21	Hydro minus wind time lag CO_2 (g-CO_2e/kWh)	3.145E+01	4.920E+01
L21=(L6+L20)*E2/10^12	Hydro-BEV CO_2 emissions (MT-CO_2e/yr)	5.917E+01	1.116E+02
L22=100*(B9-L21)/B9	Percent reduction FFOV CO_2 due to hydro-BEVs (%)	9.697E+01	9.429E+01
L23=L22*B9/B6	Percent reduction US CO_2 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 US 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 CO_2 emissions (g-CO_2e/yr)	1.148E+09	1.886E+09
M12=M11/M9	Single-CSP plant CO_2 emissions (g-CO_2e/kWh)	8.454E+00	1.133E+01
M13 (S42)	H_2O consumption wet-cool parabolic trough (gal/kWh)	7.770E-01	7.770E-01
M14=M13*M3*M6	Gal-H_2O/yr required to run US CSP-BEV	9.989E+11	1.360E+12
M15=M14/I32	Fraction of US water demand for wet-cool CSP BEV	6.708E-03	9.134E-03

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
M16=M14*F15/E2	Fraction of US 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 US CSP-BEV	1.115E+04	3.735E+04
M20=M19/E7	Fraction of US 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	CO_2 emissions due to time lag (g-CO_2e/kWh)	3.247E+01	7.102E+01
M27=M26-D20	CSP minus wind time lag CO_2 (g-CO_2e/kWh)	0.000E+00	0.000E+00
M28=(M12+M27)*E2/10^{12}	CSP-BEV CO_2 emissions (MT-CO_2e/yr)	1.033E+01	1.785E+01
M29=100*(B9-M28)/B9	Percent reduction FFOV CO_2 due to CSP-BEVs (%)	9.947E+01	9.909E+01
M30=M29*B9/B6	Percent reduction US CO_2 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

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
N7=E2/N6	Number of coal plants to run US CCS-BEV	4.631E+02	1.013E+03
N8 (S44)	Coal CO_2 direct emissions w/o CCS (g-CO_2/kWh)	7.900E+02	1.017E+03
N9 (S43)	CCS CO_2 reduction efficiency	9.000E-01	8.500E-01
N10=N8*(1–N9)	Coal CO_2 direct emissions w/CCS (g-CO_2/kWh)	7.900E+01	1.526E+02
N11(S44)	Coal non-direct lifecycle CO_2 (g-CO_2e/kWh)	1.760E+02	2.890E+02
N12=N10+N11	Total lifecycle coal-CCS CO_2 (g-CO_2e/kWh)	2.550E+02	4.416E+02
N13 (S45)	H_2O consumption from coal-fired power (gal/kWh)	4.900E-01	4.900E-01
N14=N13*N3*N7	Gal-H_2O/yr required to run US CCS-BEV	7.181E+11	1.201E+12
N15=N14/I32	Fraction of US 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 US CCS-BEV	2.397E+03	5.242E+03
N21=N20/E7	Fraction of US 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	CO_2 emissions due to time lag (g-CO_2e/kWh)	8.348E+01	1.583E+02
N28=N27-D21	Coal-CCS minus wind time lag CO_2 (g-CO_2e/kWh)	5.102E+01	8.725E+01
N29=N8-N10	CO_2 injection rate into ground (g-CO_2/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-CO_2/kWh)	1.775E+00	4.182E+01
N32=(N11+N28+N31)*E2/10^12	CCS-BEV CO_2 emissions (MT-CO_2e/yr)	3.759E+02	8.990E+02

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
N33=100*(B9–N32)/B9	Percent reduction FFOV CO_2 due to CCS-BEVs	8.077E+01	5.400E+01
N34=N33*B9/B6	Percent reduction US CO_2 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 US geo-BEV	1.513E+03	2.245E+03
O6 (S46, S47)	Geothermal lifecycle CO_2 (g-CO_2e/kWh)	1.510E+01	5.500E+01
O7 (S46)	H_2O consumption from geothermal (gal/kWh)	5.000E-03	5.000E-03
O8=O7*O3*O5	Gal-H_2O/yr required to run US geo-BEV	6.428E+09	8.753E+09
O9=O8/I32	Fraction of US 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 US geo-BEV	5.194E+02	7.072E+02
O13=O12/E7	Fraction of US 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	CO_2 emissions due to time lag (g-CO_2e/kWh)	3.348E+01	7.710E+01
O20=O19-D21	Geothermal minus wind time lag CO_2 (g-CO_2e/kWh)	1.015E+00	6.087E+00

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
O21=(O6+O20)*E2/10^12	Geo-BEV CO_2 emissions (MT-CO_2e/yr)	1.968E+01	9.624E+01
O22=100*(B9-O21)/B9	Percent reduction FFOV CO_2 due to geo-BEVs	9.899E+01	9.508E+01
O23=O22*B9/B6	Percent reduction US CO_2 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 US wave-BEV	7.703E+05	1.274E+06
P9 (S50)	Wave CO_2 emissions (g-CO_2e/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 US 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 US wave-BEV	1.926E+04	3.184E+04
P16=P15/E7	Fraction of US 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

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
P21	Time (yr) to refurbish after first lifetime	1.000E+00	2.000E+00
P22=C4*(P20+P21*100yr/ P19)/100yr	CO_2 emissions due to time lag (g-CO_2e/kWh)	5.276E+01	1.116E+02
P23=P22-D20	Wave minus wind time lag CO_2 (g-CO_2e/kWh)	2.029E+01	4.058E+01
P24=(P9+P23)*E2/10^12	Wave-BEV CO_2 emissions (MT-CO_2e/yr)	5.129E+01	9.813E+01
P25=100*(B9-P24)/B9	Percent reduction FFOV CO_2 due to wave-BEVs	9.738E+01	9.498E+01
P26=P25*B9/B6	Percent reduction US CO_2 due to wave-BEVs	3.187E+01	3.109E+01
P27 (AWEA, 2008)	Water for device manufacture (gal-H_2O/kWh)	1.000E-03	1.000E-03
P28=P27*P6*P8	Gal-H_2O/yr required to run US 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 US tidal-BEV	4.193E+05	9.992E+05
Q6 (S37)	Tidal CO_2 emissions (g-CO_2e/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 US 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 US tidal-BEV	1.553E+03	3.700E+03
Q12=Q11/E7	Fraction of US 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

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
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	CO_2 emissions due to time lag (g-CO_2e/kWh)	5.276E+01	1.116E+02
Q19=Q18-D21	Tidal minus wind time lag CO_2 (g-CO_2e/kWh)	2.029E+01	4.058E+01
Q20=(Q6+Q19)*E2/10^12	Tidal-BEV CO_2 emissions (MT-CO_2e/yr)	4.188E+01	8.599E+01
Q21=100*(B9-Q20)/B9	Percent reduction FFOV CO_2 due to tidal-BEVs	9.786E+01	9.560E+01
Q22=Q21*B9/B6	Percent reduction US CO_2 due to tidal-BEVs	3.203E+01	3.129E+01
Q23 (S19)	Water for turbine manufacture (gal-H_2O/kWh)	1.000E-03	1.000E-03
Q24=Q23*Q3*Q5	Gal-H_2O/yr required to run US tidal-BEV	1.286E+09	1.751E+09
US 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 CO_2			
S1=R1/D8	Number of turbines to displace US coal electricity	1.210E+05	1.849E+05
S2=R2/D8	Number of turbines to displace US oil electricity	3.205E+03	4.900E+03
S3=R3/D8	Number of turbines to displace US natgas electricity	5.267E+04	8.052E+04
S4=E3	Number of turbines to power US BEVs	7.298E+04	1.439E+05
S5=R5/D8	Number of turbines to displace other US sources	1.386E+05	2.299E+05

Appendix (continued)

Derivation of results used for this study

Energy required for vehicles		*Low case*	*High case*
S6=S1+S2+S3+S4+S5	Number of turbines to displace all US CO_2	3.884E+05	6.441E+05
S7=B7*S6/B6	Number of turbines to displace world CO_2	2.176E+06	3.608E+06

S1. USDT (2008).

S2. Colella et al. (2005).

S3. Onroad-vehicle CO_2 was obtained by multiplying the 1999 rate of 1370 MT-CO_2/yr from Colella et al. (2005) by the ratio of 2007 to 1999 total US petroleum CO_2 emissions from EIA (2008a). Other vehicle CO_2 was obtained by subtracting onroad-vehicle CO_2 and oil-electricity CO_2 (present table) from US petroleum CO_2.

S4. 2007 US coal, natural gas, and oil electricity CO_2 were estimated by scaling 2006 emissions from EIA (2007b) by the 2007 to 2006 ratio of total energy-related CO_2 coal, natural gas, and petroleum from EIA (2008a). 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 et al. (2008) 2004 data extrapolated to 2007 using the slope of the carbon emission change per year.

S6. Delucchi (2006).

S6. EIA (2002). Global warming potentials of 25 and 298 were applied to methane and nitrous oxide, respectively to obtain CO_2e.

S7. Archer and Jacobson (2005).

S9. RePower Systems (2008).

S10. Masters (2004); Jacobson and Masters (2001).

S11. Krohn (1997).

S12. Eberhard and Tarpenning (2006).

S13. Schultz et al. (2003).

S14. NREL (2004).

S15. Hydro-pac Inc. (2005).

S16. 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.

S17. Fthenakis and Alsema (2006), Pearce and Lau (2002), Tahara et al. (1997), and Bankier and Gale (2006).

S18. Stoddard et al. (2006).

S19. AWEA (2008).

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% (Figure 7 of Colella et al., 2005).

S21. Patzek (2006a). Also, in 2006, an average of 147.5 bushels of corn per harvested acre were produced in the US (11,800 million bushels produced on 80 million acres).

S22. USDA (2008).

S23. USDA (2003).

S24. King and Webber (2008).

S25. IATP (2006).

S26. Hutson et al. (2004).

S27. Hladik (2006).

S28. Searchinger et al. (2008).

S29. Schmer et al. (2008).

S30. European Nuclear Society (2008).

S31. IEA (2007).

S32. WNO (2008b), Sovacool (2008), IPCC (2007) and Koch (2000).

S33. EPRI (2002).

S34. Spitzley and Keoleian (2005).

S35 American Nuclear Society (2008).

S36 EIA (2006), Table 1.

S37. Tahara et al. (1997).

S38. Torcellini et al. (2003) for high value. The low value is estimated by attributing one-third of reservoir water to hydroelectric power.

S39. Low value from IPCC (2007) and Table 1 for California solar; high value from Leitner (2002).

S40. Mendax (2008).

S41. Marchie van Voorthuysen (2006).

S42. Stoddard et al. (2006) 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 of Stoddard et al.) 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) gives 0.019 km^2/MW without storage (and 0.038 km^2/MW with storage). IPCC (2007) gives 0.02 km^2/MW without storage.

S43. IPCC (2005).

S44. WNO (2008b).

S45. AWEA (2008).

S46. GEA (2008).

S47. Meier (2002).

S43. Pelamis (2008).

S49. Kane (2005).

S50. Banerjee et al. (2006)

S51. Lunar Energy (2008).

S52. Ocean Energy Council (2008).

S53. EIA (2008b).