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Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials

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ABSTRACT

Climate change, pollution, and energy insecurity are among the greatest problems of our time. Addressing them requires major changes in our energy infrastructure. Here, we analyze the feasibility of providing worldwide energy for all purposes (electric power, transportation, heating/cooling, etc.) from wind, water, and sunlight (WWS). In Part I, we discuss WWS energy system characteristics, current and future energy demand, availability of WWS resources, numbers of WWS devices, and area and material requirements. In Part II, we address variability, economics, and policy of WWS energy. We estimate that ~3,800,000 5 MW wind turbines, ~49,000 300 MW concentrated solar plants, ~40,000 300 MW solar PV power plants, ~1.7 billion 3 kW rooftop PV systems, ~5350 100 MW geothermal power plants, ~270 new 1300 MW hydroelectric power plants, ~720,000 0.75 MW wave devices, and ~490,000 1 MW tidal turbines can power a 2030 WWS world that uses electricity and electrolytic hydrogen for all purposes. Such a WWS infrastructure reduces world power demand by 30% and requires only ~0.41% and ~0.59% more of the world's land for footprint and spacing, respectively. We suggest producing all new energy with WWS by 2030 and replacing the pre-existing energy by 2050. Barriers to the plan are primarily social and political, not technological or economic. The energy cost in a WWS world should be similar to that today.

1. Introduction

A solution to the problems of climate change, air pollution, water pollution, and energy insecurity requires a large-scale conversion to clean, perpetual, and reliable energy at low cost together with an increase in energy efficiency. Over the past decade, a number of studies have proposed large-scale renewable energy plans. Jacobson and Masters (2001) suggested that the U.S. could satisfy its Kyoto Protocol requirement for reducing carbon dioxide emissions by replacing 60% of its coal generation with 214,000–236,000 wind turbines rated at 1.5 MW (million watts). Also in 2001, Czisch (2006) suggested that a totally renewable electricity supply system, with intercontinental transmission lines linking dispersed wind sites with hydropower backup, could supply Europe, North Africa, and East Asia at total costs per kWh comparable with the costs of the current system. Hoffert et al. (2002) suggested a portfolio of solutions for stabilizing atmospheric CO_2, including increasing the use of renewable energy and nuclear energy, decarbonizing fossil fuels and sequestering carbon, and improving energy efficiency. Pacala and Socolow (2004) suggested a similar portfolio, but expanded it to include reductions in deforestation and conservation tillage and greater use of hydrogen in vehicles.

More recently, Fthenakis et al. (2009) analyzed the technical, geographical, and economic feasibility for solar energy to supply the energy needs of the U.S. and concluded (p. 397) that "it is clearly feasible to replace the present fossil fuel energy infrastructure in the U.S. with solar power and other renewables, and reduce CO_2 emissions to a level commensurate with the most aggressive climate-change goals". Jacobson (2009) evaluated several long-term energy systems according to environmental and other criteria, and found WWS systems to be superior to nuclear, fossil-fuel, and biofuel systems (see further discussion in Section 2). He proposed to address the hourly and seasonal variability of WWS power by interconnecting geographically disperse renewable energy sources to smooth out loads, using hydroelectric power to fill in gaps in supply. He also proposed using battery-electric vehicles (BEVs) together with utility controls of electricity dispatch to them through smart meters, and storing electricity in hydrogen or solar-thermal storage media. Cleetus et al. (2009) subsequently presented a "blueprint" for a clean-energy economy to reduce CO_2-equivalent GHG emissions in the U.S. by 56% compared with the 2005 levels. That study featured an economy-wide CO_2

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Table 1
Recent studies of rapid, large-scale development of renewable energy.

Study	Energy mix by sector		Time frame	Geographic scope
This study and Jacobson and Delucchi (2009)	Electricity transport heat/cool	100% WWS	All new energy: 2030. All energy: 2050	World
Alliance for Climate Protection (2009)	Electricity transport	100% WWS+Bm	2020	U.S.
Parsons-Brinckerhoff (2009)	Electricity transport heat/cool	80% WWS+NCBmBf	2050	UK
Price-Waterhouse-Coopers (2010)	Electricity	100% WWS+Bm	2050	Europe & North Africa
Beyond Zero Emissions (2010)	Electricity transport heat/cool	100% WWS+Bm	2020	Australia
European Climate Foundation (ECF) (2010)	Electricity transport heat/cool	80% WWS+NCBm	2050	Europe
European Renewable Energy Council (EREC) (April (2010)	Electricity transport heat/cool	100% WWS+BmBf	2050	Europe

WWS = wind, water, solar power; FF = fossil fuels; Bm = biomass; Bf = liquid biofuels; N = nuclear; C = coal-CCS. Cleetus et al. (2009) is not included only because its focus is mainly on efficiency and demand management, with only modest increases in renewable energy.

cap-and-trade program and policies to increase energy efficiency and the use of renewable energy in industry, buildings, electricity, and transportation. Sovacool and Watts (2009) suggested that a completely renewable electricity sector for New Zealand and the United States is feasible.

In Jacobson and Delucchi (2009), we outlined a large-scale plan to power the world for all purposes with WWS (no biofuels, nuclear power, or coal with carbon capture). The study found that it was technically feasible to power the world with WWS by 2030 but such a conversion would almost certainly take longer due to the difficulty in implementing all necessary policies by then. However, we suggested, and this study reinforces, the concept that all new energy could be supplied by WWS by 2030 and all existing energy could be converted to WWS by 2050. The analysis presented here is an extension of that work.

Table 1 compares and summarizes several other recent large-scale plans. While all plans are ambitious, forward thinking, and detailed, they differ from our plan, in that they are for limited world regions and none relies completely on WWS. However, some come close in the electric power sector, relying on only small amounts of non-WWS energy in the form of biomass for electric power production. Those studies, however, address only electricity and/or transport, but not heating/cooling.

More well known to the public than the scientific studies, perhaps, are the "Repower America" plan of former Vice-President and Nobel-Peace Prize winner Al Gore, and a similar proposal by businessman T. Boone Pickens. Mr. Gore's proposal calls for improvements in energy efficiency, expansion of renewable energy generation, modernization of the transmission grid, and the conversion of motor vehicles to electric power. The ultimate (and ambitious) goal is to provide America "with 100% clean electricity within 10 years," which Mr. Gore proposes to achieve by increasing the use of wind and concentrated solar and improving energy efficiency (Alliance for Climate Protection, 2009). In Gore's plan, solar PV, geothermal, and biomass electricity would grow only modestly, and nuclear power and hydroelectricity would not grow. Mr. Pickens' plan is to obtain up to 22% of the U.S. electricity from wind, add solar capacity to that, improve the electric grid, increase energy efficiency, and use natural gas instead of oil as a transitional fuel (Pickens, 2009).

There is little doubt that the large-scale use of renewable energy envisaged in these plans and studies would greatly mitigate or eliminate a wide range of environmental and human health impacts of energy use (e.g., Jacobson, 2009; Sovacool and Sovacool, 2009; Colby et al., 2009; Weisser, 2007; Fthenakis and Kim, 2007). But, is a large-scale transformation of the world's energy systems feasible? In this paper and in Part II, we address this question by examining the characteristics and benefits of wind, water, and solar (WWS)-energy systems, the availability of WWS resources, supplies of critical materials, methods of addressing the variability of WWS energy to ensure that power supply reliably matches demand, the economics of WWS generation and transmission, the economics of the use of WWS power in transportation, and policy issues. Although we recognize that a comprehensive plan to address global environmental problems must also address other sectors, including agriculture (Horrigan et al., 2002; Wall and Smit, 2005) and forestry (Niles et al., 2002), we do not address those issues here.

2. Clean, low-risk, sustainable energy systems

2.1. Evaluation of long-term energy systems: why we choose WWS power

Because climate change (particularly loss of the Arctic sea ice cap), air pollution, and energy insecurity are the current and growing problems, but it takes several decades for new technologies to become fully adopted, we consider only options that have been demonstrated in at least pilot projects and that can be scaled up as part of a global energy system without further major technology development. We avoid options that require substantial further technological development and that will not be ready to begin the scale-up process for several decades. Note that we select technologies based on the state of development of the technology only rather than whether industrial capacity is currently ramped up to produce the technologies on a massive scale or whether society is motivated to change to the technologies. In this paper and in Part II, we do consider the feasibility of implementing the chosen technologies based on estimated costs, necessary policies, and available materials as well as other factors.

In order to ensure that our energy system remains clean even with large increases in population and economic activity in the long run, we consider only those technologies that have essentially zero emissions of greenhouse gases and air pollutants per unit of output over the whole "lifecycle" of the system. Similarly, we consider only those technologies that have low impacts on wildlife, water pollution, and land, do not have significant waste-disposal or terrorism risks associated with them, and are based on primary resources that are indefinitely renewable or recyclable.

The previous work by Jacobson (2009) indicates that WWS power satisfies all of these criteria. He ranked several long-term energy systems with respect to their impacts on global warming, air pollution, water supply, land use, wildlife, thermal pollution, water–chemical pollution, and nuclear weapons proliferation. The ranking of electricity options, starting with the highest, included: wind power, concentrated solar, geothermal, tidal, solar photovoltaic, wave, and hydroelectric power, all of which are powered by wind, water, or sunlight (WWS). He also found that the use of BEVs and hydrogen fuel-cell vehicles (HFCVs) powered by the WWS options would largely eliminate pollution from the transportation sector. Here, we consider these technologies and other existing technologies for the heating/cooling sectors, discussed in Section 2. Although other clean WWS electric power sources, such as ocean or river current power, could be deployed in the short term, these are not examined here simply because we could not cover every technology. Nevertheless, we do cover related although slightly different power sources (e.g., wave, tidal, and hydroelectric power).

Finally, Jacobson (2009) concluded that coal with carbon capture, corn ethanol, cellulosic ethanol, and nuclear power were all moderately or significantly worse than WWS options with respect to environmental and land use impacts. Similarly, here we do not consider any combustion sources, such as coal with carbon capture, corn ethanol, cellulosic ethanol, soy biodiesel, algae biodiesel, biomass for electricity, other biofuels, or natural gas, because none of these technologies can reduce GHG and air-pollutant emissions to near zero, and all can have significant problems in terms of land use, water use, or resource availability (See Delucchi (2010) for a review of land-use, climate-change, and water-use impacts of biofuels.) For example, even the most climate-friendly and ecologically acceptable sources of ethanol, such as unmanaged, mixed grasses restored to their native (non-agricultural) habitat (Tilman et al., 2006), will cause air pollution mortality on the same order as gasoline (Jacobson, 2007; Anderson, 2009; Ginnebaugh et al., 2010). The use of carbon capture and sequestration (CCS) can reduce CO_2 emissions from the stacks of coal power plants by 85–90% or more, but it has no effect on CO_2 emissions due to the mining and transport of coal; in fact it will *increase* such emissions and of air pollutants per unit of net delivered power and will increase all ecological, land-use, air-pollution, and water-pollution impacts from coal mining, transport, and processing, because the CCS system requires 25% more energy, thus 25% more coal combustion, than does a system without CCS (IPCC, 2005).

For several reasons we do not consider nuclear energy (conventional fission, breeder reactors, or fusion) as a long-term global energy source. First, the growth of nuclear energy has historically increased the ability of nations to obtain or enrich uranium for nuclear weapons (Ullom, 1994), and a large-scale worldwide increase in nuclear energy facilities would exacerbate this problem, putting the world at greater risk of a nuclear war or terrorism catastrophe (Kessides, 2010; Feiveson, 2009; Miller and Sagan, 2009; Macfarlane and Miller, 2007; Harding, 2007). The historic link between energy facilities and weapons is evidenced by the development or attempted development of weapons capabilities secretly in nuclear energy facilities in Pakistan, India (Federation of American Scientists, 2010), Iraq (prior to 1981), Iran (e.g., Adamantiades and Kessides, 2009, p. 16), and to some extent North Korea. Feiveson (2009) writes that "it is well understood that one of the factors leading several countries now without nuclear power programs to express interest in nuclear power is the foundation that such programs could give them to develop weapons" (p. 65). Kessides (2010) asserts, "a robust global expansion of civilian nuclear power will significantly increase proliferation risks unless the current non-proliferation regime is substantially strengthened by technical and institutional measures and its international safeguards system adequately meets the new challenges associated with a geographic spread and an increase in the number of nuclear facilities" (p. 3860). Similarly, Miller and Sagan (2009) write, "it seems almost certain that some new entrants to nuclear power will emerge in the coming decades and that the organizational and political challenges to ensure the safe and secure spread of nuclear technology into the developing world will be substantial and potentially grave" (p. 12).

If the world were converted to electricity and electrolytic hydrogen by 2030, the 11.5 TW in resulting power demand would require ~15,800 850 MW nuclear power plants, or one installed every day for the next 43 years. Even if only 5% of these were installed, that would double the current installations of nuclear power worldwide. Many more countries would possess nuclear facilities, increasing the likelihood that these countries would use the facilities to hide the development of nuclear weapons as has occurred historically.

Second, nuclear energy results in 9–25 times more carbon emissions than wind energy, in part due to emissions from uranium refining and transport and reactor construction (e.g., Lenzen, 2008; Sovacool, 2008), in part due to the longer time required to site, permit, and construct a nuclear plant compared with a wind farm (resulting in greater emissions from the fossil-fuel electricity sector during this period; Jacobson, 2009), and in part due to the greater loss of soil carbon due to the greater loss in vegetation resulting from covering the ground with nuclear facilities relative to wind turbine towers, which cover little ground. Although recent construction times worldwide are shorter than the 9-year median construction times in the U.S. since 1970 (Koomey and Hultman, 2007), they still averaged 6.5 years worldwide in 2007 (Ramana, 2009), and this time must be added to the site permit time (~3 years in the U.S.) and construction permit and issue time (~3 years). The overall historic and present range of nuclear planning-to-operation times for new nuclear plants has been 11–19 years, compared with an average of 2–5 years for wind and solar installations (Jacobson, 2009). Feiveson (2009) observes that "because wind turbines can be installed much faster than could nuclear, the cumulative greenhouse gas savings per capital invested appear likely to be greater for wind" (p. 67). The long time required between planning and operation of a nuclear power plant poses a significant risk to the Arctic sea ice. Sea ice records indicate a 32% loss in the August 2010 sea ice area relative to the 1979–2008 mean (Cryosphere Today, 2010). Such rapid loss indicates that solutions to global warming must be implemented quickly. Technologies with long lead times will allow the high-albedo Arctic ice to disappear, triggering more rapid positive feedbacks to warmer temperatures by uncovering the low-albedo ocean below.

Third, conventional nuclear fission relies on finite stores of uranium that a large-scale nuclear program with a "once through" fuel cycle would exhaust in roughly a century (e.g., Macfarlane and Miller, 2007; Adamantiades and Kessides, 2009). In addition, accidents at nuclear power plants have been either catastrophic (Chernobyl) or damaging (Three-Mile Island), and although the nuclear industry has improved the safety and performance of reactors, and has proposed new (but generally untested) "inherently" safe reactor designs (Piera, 2010; Penner et al., 2008; Adamantiades and Kessides, 2009; Mourogov et al., 2002; Mourogov, 2000), there is no guarantee that the reactors will be designed, built, and operated correctly. For example, Pacific Gas and Electric Company had to redo some modifications it made to its Diablo Canyon nuclear power plant after the original work was done backwards (Energy Net, 2010), and French nuclear regulators recently told the firm Areva to correct a safety design flaw in its latest-generation reactor (Nuclear Power Daily, 2009). Further, catastrophic scenarios involving terrorist attacks are still conceivable (Feiveson, 2009). Even if the risks of catastrophe are very small, they are not zero (Feiveson, 2009), whereas with wind and solar power, the risk of catastrophe *is* zero. Finally, conventional nuclear power produces radioactive waste, which must be stored for thousands of years, raising technical and long-term cost questions (Barré, 1999; von Hippel, 2008; Adamantiades and Kessides, 2009).

"Breeder" nuclear reactors have similar problems as conventional fission reactors, except that they produce less low-level radioactive waste than do conventional reactors and re-use the spent fuel, thereby extending uranium reserves, perhaps indefinitely (Penner et al., 2008; Purushotham et al., 2000; Till et al., 1997). However, they produce nuclear material closer to weapons grade that can be reprocessed more readily into nuclear weapons (Kessides, 2010; Adamantiades and Kessides, 2009; Macfarlane and Miller, 2007; Glaser and Ramana, 2007), although some technologies have technical features that make diversion and reprocessing especially difficult—albeit not impossible (Hannum et al., 1997; Kessides, 2010; Penner et al., 2008). Kessides (2010) writes, "analyses of various reactor cycles have shown that all have some potential for diversion, i.e., there is no proliferation-proof nuclear power cycle" (p. 3861).

A related proposal is to use thorium as a nuclear fuel, which is less likely to lead to nuclear weapons proliferation than the use of uranium, produces less long-lived radioactive waste, and greatly extends uranium resources (Macfarlane and Miller, 2007). However, thorium reactors require the same significant time lag between planning and operation as conventional uranium reactors and most likely longer because few developers and scientists have experience with constructing or running thorium reactors. As such, this technology will result in greater emissions from the background electric grid compared with WWS technologies, which have a shorter time lag. In addition, lifecycle emissions of carbon from a thorium reactor are on the same order as those from a uranium reactor. Further, thorium still produces radioactive waste containing ^{231}Pa, which has a half-life of 32,760 years. It also produces ^{233}U, which can be used in fission weapons, such as in one nuclear bomb core during the Operation Teapot nuclear tests in 1955. Weaponization, though, is made more difficult by the presence of ^{232}U.

Fusion of light atomic nuclei (e.g., protium, deuterium, or tritium) theoretically could supply power indefinitely without long-lived radioactive wastes as the products are isotopes of helium (Ongena and Van Oost, 2006; Tokimatsu et al., 2003); however, it would produce short-lived waste that needs to be removed from the reactor core to avoid interference with operations, and it is unlikely to be commercially available for at least another 50–100 years (Tokimatsu et al., 2003; Barré, 1999; Hammond, 1996), long after we will have needed to transition to alternative energy sources. By contrast, wind and solar power are available today, will last indefinitely, and pose no serious risks. Note that our reasons for excluding nuclear are not economic. A brief discussion of the economics of nuclear power is given in Appendix A.

For these reasons, we focus on WWS technologies. We assume that WWS will supply electric power for the transportation, heating (including high-temperature heating and cooking)/cooling sectors, which traditionally have relied mainly on the direct use of oil or gas rather than electricity, as well as for traditional electricity-consuming end uses such as lighting, cooling, manufacturing, motors, electronics, and telecommunications. Although we focus mainly on energy *supply,* we acknowledge and indeed emphasize the importance of demand-side energy conservation measures to reduce the requirements and impacts of energy supply. Demand-side energy-conservation measures include improving the energy-out/energy-in efficiency of end uses (e.g., with more efficient vehicles, more efficient lighting, better insulation in homes, and the use of heat-exchange and filtration systems), directing demand to low-energy-use modes (e.g., using public transit or telecommuting instead of driving), large-scale planning to reduce energy demand without compromising economic activity or comfort (e.g., designing cities to facilitate greater use of non-motorized transport and to have better matching of origins and destinations, thereby reducing the need for travel), and designing buildings to use solar energy directly (e.g., with more daylighting, solar hot water heating, and improved passive solar heating in winter and cooling in summer). For a general discussion of the potential to reduce energy use in transportation and buildings, see the American Physical Society (2008). For a classification scheme that facilitates analyses of the potential gains from energy efficiency, see Cullen and Allwood (2009).

2.2. *Characteristics of electricity-generating WWS technologies*

2.2.1. *Wind*

Wind turbines convert the energy of the wind into electricity. Generally, a gearbox turns the slow-moving turbine rotor into faster-rotating gears, which convert mechanical energy to electricity in a generator. Some modern turbines are gearless. Although less efficient, small turbines can be used in homes or buildings. Wind farms today appear on land and offshore, with individual turbines ranging in size up to 7 MW, with 10 MW planned. High-altitude wind energy capture is also being pursued today by several companies.

2.2.2. *Wave*

Winds passing over water create surface waves. The faster the wind speed, the longer the wind is sustained, the greater the distance the wind travels, the greater the wave height, and the greater the wave energy produced. Wave power devices capture energy from ocean surface waves to produce electricity. One type of device is a buoy that rises and falls with a wave. Another type is a surface-following device, whose up-and-down motion increases the pressure on oil to drive a hydraulic motor.

2.2.3. *Geothermal*

Steam and hot water from below the Earth's surface have been used historically to provide heat for buildings, industrial processes, and domestic water and to generate electricity in geothermal power plants. In power plants, two boreholes are drilled—one for steam alone or liquid water plus steam to flow up, and the second for condensed water to return after it passes through the plant. In some plants, steam drives a turbine; in others, hot water heats another fluid that evaporates and drives the turbine.

2.2.4. *Hydroelectricity*

Water generates electricity when it drops gravitationally, driving a turbine and generator. While most hydroelectricity is produced by water falling from dams, some is produced by water flowing down rivers (run-of-the-river electricity).

2.2.5. *Tidal*

A tidal turbine is similar to a wind turbine in that it consists of a rotor that turns due to its interaction with water during the ebb and flow of a tide. Tidal turbines are generally mounted on the sea floor. Since tides run about 6 h in one direction before switching directions for 6 h, tidal turbines can provide a predictable energy source. O'Rourke et al. (2010) provide an excellent overview of the technology of tidal energy.

2.2.6. *Solar PV*

Solar photovoltaics (PVs) are arrays of cells containing a material, such as silicon, that converts solar radiation into electricity. Today, solar PVs are used in a wide range of applications, from residential rooftop power generation to medium-scale utility-level power generation.

2.2.7. *CSP*

Concentrated solar power (CSP) systems use mirrors or reflective lenses to focus sunlight on a fluid to heat it to a high temperature. The heated fluid flows from the collector to a heat engine where a portion of the heat is converted to electricity. Some types of CSP allow the heat to be stored for many hours so that electricity can be produced at night.

2.3. Use of WWS power for transportation

Transportation technologies that must be deployed on a large scale to use WWS-power include primarily battery-electric vehicles (BEVs), hydrogen fuel-cell vehicles (HFCVs), and hybrid BEV-HFCVs. For ships, we propose the use of hybrid hydrogen fuel cell-battery systems, and for aircraft, liquefied hydrogen combustion (Appendix A).

BEVs store electricity in and draw power from batteries to run an electric motor that drives the vehicle. So long as the electricity source is clean, the BEV system will have zero emissions of air pollutants and greenhouse gases over the entire energy lifecycle—something that internal-combustion-engine vehicles (ICEVs) using liquid fuels cannot achieve. Moreover, BEVs provide up to 5 times more work in distance traveled per unit of input energy than do ICEVs (km/kWh-outlet versus km/kWh-gasoline). BEVs have existed for decades in small levels of production, but today most major automobile companies are developing BEVs. The latest generation of vehicles uses lithium-ion batteries, which do not use the toxic chemicals associated with lead-acid or the nickel-cadmium batteries.

Hydrogen fuel cell vehicles (HFCVs) use a fuel cell to convert hydrogen fuel and oxygen from the air into electricity that is used to run an electric motor. HFCVs are truly clean only if the hydrogen is produced by passing WWS-derived electricity through water (electrolysis). Thus, we propose producing hydrogen only in this way. Several companies have prototype HFCVs, and California had about 200 HFCVs on the road in 2009 (California Fuel Cell Partnership, 2009). Hydrogen fueling stations, though, are practically non-existent and most hydrogen today is produced by steam-reforming of natural gas, which is not so clean as hydrogen produced by WWS-electrolysis.

2.4. Use of WWS power for heating and cooling

For building water and air heating using WWS power, we propose the use of air- and ground-source heat-pump water and air heaters and electric resistance water and air heaters. Heat pump air heaters also can be used in reverse for air conditioning. These technologies exist today although in most places they satisfy less demand than do natural gas or oil-fired heaters. The use of electricity for heating and cooking, like the use of electricity for transportation, is most beneficial when the electricity comes from WWS. For high-temperature industrial processes, we propose that energy be obtained by combustion of electrolytic hydrogen (Appendix A).

3. Energy resources needed and available

The power required today to satisfy all end uses worldwide is about 12.5 trillion watts (TW) (EIA, 2008a; end-use energy only, excludes losses in production and transmission). In terms of primary energy, about 35% is from oil, 27% from coal, 23% from natural gas, 6% from nuclear, and the rest from biomass, sunlight, wind, and geothermal. Delivered electricity is a little over 2 TW of the end-use total.

The EIA (2008a) projects that in the year 2030, the world will require almost 17 TW in end-use power, and the U.S. almost 3 TW (Table 2). They also project that the breakdown in terms of primary energy in 2030 will be similar to that today—heavily dependent on fossil fuels, and hence almost certainly unsustainable. What would world power demand look like if instead a sustainable WWS system supplied all end-use energy needs?

Table 2
Projected end-use power in 2030, by sector, U.S. and the world, conventional fossil-fuel case, and replacing 100% of fossil fuel and wood combustion with WWS.

Energy sector, by EIA energy-use categories	TW power in 2030 (conventional fossil fuels)		Elect. fract.	End-use energy/work w.r.t. fossil fuel		Upstream factor	EHCM factor	TW power in 2030 replacing all fossil fuels with WWS	
	World	*U.S.*		*Electric*	*e-H$_2$*			*World*	*U.S.*
Residential									
Liquids	0.37	0.04	0.95	0.82	1.43	1.00	0.90	0.29	0.03
Natural gas	0.84	0.18	0.95	0.82	1.43	1.00	0.90	0.61	0.13
Coal	0.11	0.00	1.00	0.82	1.43	1.00	0.90	0.08	-
Electricity	0.92	0.20	1.00	1.00	1.00	1.00	0.95	0.83	0.18
Renewables	0.02	0.01	0.50	0.82	1.43	1.00	0.90	0.02	0.01
Total	**2.26**	**0.43**						**1.83**	**0.35**
Commercial									
Liquids	0.18	0.02	0.90	0.82	1.43	1.00	0.95	0.15	0.02
Natural gas	0.32	0.13	0.90	0.82	1.43	1.00	0.95	0.26	0.10
Coal	0.03	0.00	0.90	0.82	1.43	1.00	0.95	0.03	0.00
Electricity	0.78	0.22	1.00	1.00	1.00	1.00	1.00	0.78	0.22
Renewables	0.01	0.00	0.90	0.82	1.43	1.00	0.95	0.01	0.00
Total	**1.32**	**0.38**						**1.22**	**0.35**
Industrial									
Liquids	2.41	0.31	0.60	0.82	1.43	0.72	0.95	1.76	0.22
Natural gas	2.35	0.28	0.60	0.82	1.43	0.82	0.95	1.95	0.23
Coal	2.15	0.08	0.60	0.82	1.43	0.73	0.95	1.59	0.06
Electricity	1.75	0.12	1.00	1.00	1.00	0.93	1.00	1.62	0.11
Renewables	0.15	0.14	0.90	0.82	1.43	1.00	0.95	0.13	0.12
Total	**8.80**	**0.92**						**7.05**	**0.74**
Transportation									
Liquids	4.44	1.07	0.73	0.19	0.64	1.18	0.85	1.30	0.31
Natural gas	0.05	0.03	0.90	0.82	1.43	1.00	0.85	0.04	0.02
Coal	–	0.00	0.90	0.82	1.43	1.00	0.85	–	–
Electricity	0.04	0.00	1.00	1.00	1.00	1.00	0.95	0.03	–
Total	**4.53**	**1.10**						**1.37**	**0.33**
Total end uses	**16.92**	**2.83**						**11.47**	**1.78**

Notes: see Appendix A.2.

Table 2 shows our estimates of global and U.S. end-use energy demand, by sector, in a world powered entirely by WWS, with zero fossil-fuel and biomass combustion. We have assumed that all end uses that feasibly can be electrified use WWS power directly, and that the remaining end uses use WWS power indirectly in the form of electrolytic hydrogen (hydrogen produced by splitting water with WWS power). As explained in Section 2 we assume that most uses of fossil fuels for heating/cooling can be replaced by electric heat pumps, and that most uses of liquid fuels for transportation can be replaced by BEVs. The remaining, non-electric uses can be supplied by hydrogen, which we assume would be compressed for use in fuel cells in remaining non-aviation transportation, liquefied and combusted in aviation, and combusted to provide heat directly in the industrial sector. The hydrogen would be produced using WWS power to split water; thus, directly or indirectly, WWS powers the world.

As shown in Table 2, the direct use of electricity, for example, for heating or electric motors, is considerably more efficient than is fuel combustion in the same application. The use of electrolytic hydrogen is less efficient than is the use of fossil fuels for direct heating but more efficient for transportation when fuel cells are used; the efficiency difference between direct use of electricity and electrolytic hydrogen is due to the energy losses of electrolysis, and in the case of most transportation uses, the energy requirements of compression and the greater inefficiencies of fuel cells than batteries. Assuming that some additional modest energy-conservation measures are implemented (see the list of demand-side conservation measures in Section 2) and subtracting the energy requirements of petroleum refining, we estimate that an all-WWS world would require ~30% less end-use power than the EIA projects for the conventional fossil-fuel scenario (Table 1).

How do the energy requirements of a WWS world, shown in Table 2, compare with the availability of WWS power? Table 3 gives the estimated power available worldwide from renewable energy, in terms of raw resources, resources available in high-energy locations, resources that can feasibly be extracted in the near term considering cost and location, and the current resources used. The table indicates that only solar and wind can provide more power on their own than energy demand worldwide. Wind in developable locations can power the world about 3–5 times over and solar, about 15–20 times over.

Fig. 1 shows the modeled world wind resources at 100 m, in the range of the hub height of modern wind turbines. Globally, ~1700 TW of wind energy are available over the world's land plus ocean surfaces at 100 m if all wind at all speeds were used to power wind turbines (Table 3); however, the wind power over land in locations over land and near shore where the wind speed is 7 m/s or faster (the speed necessary for cost-competitive wind energy) is around 72–170 TW (Archer and Jacobson, 2005; Lu et al., 2009; Fig. 1). Over half of this power is in locations that could practically be developed. Large regions of fast winds worldwide include the Great Plains of the U.S. and Canada, Northern Europe, the Gobi and Sahara Deserts, much of the Australian desert areas, and parts of South Africa and Southern South America and South Africa. In the U.S., wind from the Great Plains and offshore the East Coast (Kempton et al., 2007) could supply all U.S. energy needs. Other windy offshore regions include the North Sea, the West Coast of the U.S. (Dvorak et al., 2010), and the East Coast of Asia among others.

Extraction from the wind of 100% of the power needed for the world in 2030 (11.5 TW from Table 2) would reduce the overall power in the wind at 100 m by $<1\%$ (Santa Maria and Jacobson, 2009). Such extracted power is eventually dissipated to heat, a portion of which is cycled back to produce more potential energy, which produces kinetic energy, regenerating some of the wind. The remaining heat goes toward slightly increasing air and ground temperature, but this addition is very small. For example, the maximum additional radiative forcing due to powering the world with wind is $\sim 11.5\ \text{TW}/5.106\times10^{14}\ \text{m}^2$ (area of the Earth) $=0.022$ W/m^2, which is only ~0.7% of the ~3 W/m^2 forcing due to all

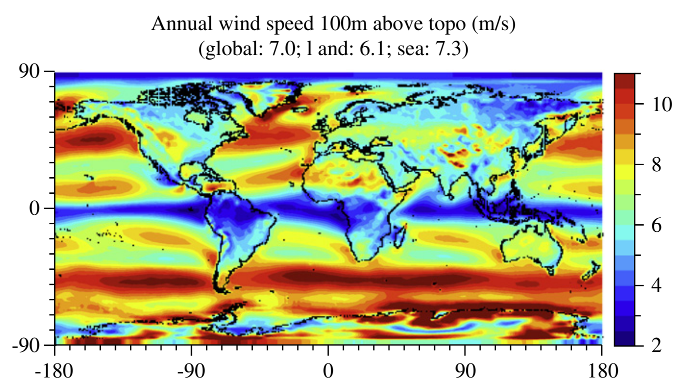

Fig. 1. Map of the yearly averaged world wind speed (m/s) at 100 m above sea level at $1.5\times1.5^\circ$ resolution, generated with the GATOR-GCMOM 3-D global model (Jacobson, 2010).

Table 3
Power available in energy resource worldwide if the energy is used in conversion devices, in locations where the energy resource is high, in likely-developable locations, and in delivered electricity in 2005 or 2007 (for wind and solar PV).

Energy technology	Power worldwide (TW)	Power in high-energy locations (TW)	Power in likely-developable locations (TW)	Current power delivered as electricity (TW)
Wind	1700[a]	72–170[b]	40–85[c]	0.02[d]
Wave	>2.7[d]	2.7[e]	0.5[d]	0.000002[d]
Geothermal	45[f]	2[g]	0.07-0.14[d]	0.0065[d]
Hydroelectric	1.9[d]	<1.9[d]	1.6[d]	0.32[d]
Tidal	3.7[d]	0.8[d]	0.02[d]	0.00006[d]
Solar PV	6500[h]	1300[i]	340[d]	0.0013[d]
CSP	4600[j]	920[j]	240[j]	000046[d]

[a] Fig. 1 here; accounts for all wind speeds at 100 m over land and ocean.
[b] Locations over land or near the coast where the mean wind speed ≥ 7 m/s at 80 m (Archer and Jacobson, 2005) and at 100 m (Lu et al, 2009; Fig. 1 here).
[c] Eliminating remote locations.
[d] Jacobson (2009) and references therein.
[e] Wave power in coastal areas.
[f] Fridleifsson et al. (2008).
[g] Includes estimates of undiscovered reservoirs over land.
[h] Fig. 2 here, assuming use of 160 W solar panels and areas determined in Jacobson (2009), over all latitudes, land, and ocean.
[i] Same as (h) but locations over land between 50S and 50N.
[j] Scaling solar PV resource with relative land area requirements from Jacobson (2009).

greenhouse gases. Since wind turbines replace other electricity sources that also produce heat in this manner (Santa Maria and Jacobson, 2009), wind turbines (and other renewable electricity sources) replacing current infrastructure cause no net heat addition to the atmosphere. They serve only to reduce global-warming pollutants and heath-affecting air pollutants that current electricity and energy sources produce.

Fig. 2 shows the distribution of solar energy at the Earth's surface. Globally, 6500 TW of solar energy are available over the world's land plus ocean surfaces if all sunlight is used to power photovoltaics (Table 3); however, the deliverable solar power over land in locations where solar PV could practically be developed is about 340 TW. Alternatively CSP could provide about 240 TW of the world's power output, less than PV since the land area required for CSP without storage is about one-third greater than is that for PV. With thermal storage, the land area for CSP increases since more solar collectors are needed to provide energy for storage, but energy output does not change and the energy can be used at night. However, water-cooled CSP plants can require water for cooling during operation (about 8 gal/kWh—much more than PVs and wind (~0 gal/kWh), but less than nuclear and coal (~40 gal/kWh) (Sovacool and Sovacool, 2009)), and this might be a constraint in some areas. This constraint is not accounted for in the estimates of Table 3. However, air-cooled CSP plants require over 90% less water than water-cooled plants at the cost of only about 5% less electric power and 2–9% higher electricity rates (USDOE, 2008b), suggesting air-cooled plants may be a viable alternative in water-limited locations.

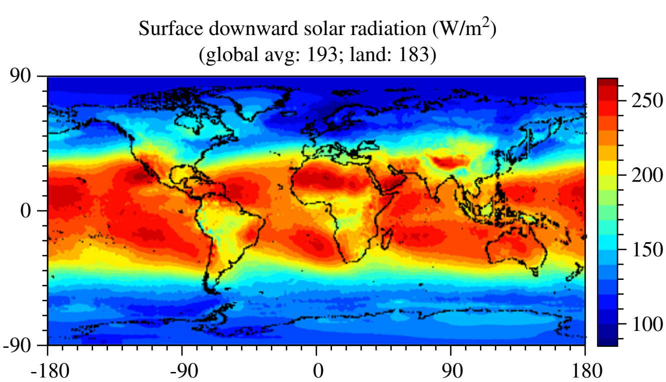

Fig. 2. Map of the yearly averaged downward surface solar radiation reaching the surface (W/m^2) at $1.5 \times 1.5^\circ$ resolution, generated with the GATOR-GCMOM 3-D global model (Jacobson, 2010).

The other WWS technologies have much less resource availability than do wind, CSP, and PV (Table 3), yet can still contribute beneficially to the WWS solution. Wave power can be extracted practically only near coastal areas, which limits its worldwide potential. Although the Earth has a very large reservoir of geothermal energy below the surface, most of it is too deep to extract practically. Even though hydroelectric power today exceeds all other sources of WWS power, its future potential is limited because most of the large reservoirs suitable for generating hydropower are already in use.

Further, although there is enough feasibly developable wind and solar power to supply the world, other WWS resources will be more abundant and more economical than wind and solar in many locations. Finally, wind and solar power are variable, so geothermal and tidal power, which provide relatively constant power, and hydroelectric, which fills in gaps, will be important for providing a stable electric power supply.

See a detailed discussion of this in Part II of this work, Delucchi and Jacobson (this issue).

4. Quantities and areas of plants and devices required

How many WWS power plants or devices are required to power the world and U.S.? Table 4 provides an estimate for 2030, assuming a given fractionation of the demand (from Table 2) among technologies. Wind and solar together are assumed to comprise 90% of the future supply based on their relative abundances (Table 3). Although 4% of the proposed future supply is hydro, most of this amount (70%) is already in place. Solar PV is divided into 30% rooftop, based on an analysis of likely available rooftop area (Jacobson, 2009) and 70% power plant. Rooftop PV has three major advantages over power-plant PV: rooftop PV does not require an electricity transmission and distribution network, it can be integrated into a hybrid solar system that produces heat, light, and electricity for use on site (Chow, 2010), and it does not require new land area. Table 4 suggests that almost 4 million 5 MW wind turbines (over land or water) and about 90,000 300 MW PV plus CSP power plants are needed to help power the world. Already, about 0.8% of the wind is installed.

The total footprint on the ground (for the turbine tubular tower and base) for the 4 million wind turbines required to power 50% of the world's energy is only $\sim$48 km^2, smaller than Manhattan (59.5 km^2) whereas the spacing needed between turbines to

Table 4
Number of WWS power plants or devices needed to power the world and U.S. total energy demand in 2030 (11.5 and 1.8 TW, respectively, from Table 2), assuming a given partitioning of the demand among plants or devices. Also shown are the footprint and spacing areas required to power the world, as a percentage of the global land area, 1.446×10^8 km^2. Derived from appendix A of Jacobson (2009).

Energy technology	Rated power of one plant or device (MW)	Percent of 2030 power demand met by plant/device	Number of plants or devices needed World	Footprint area (% of global land area)	Spacing area (% of global land area)	Number of plants or devices needed U.S.
Wind turbine	5	50	3.8 million	0.000033	1.17	590,000
Wave device	0.75	1	720,000	0.00026	0.013	110,000
Geothermal plant	100	4	5350	0.0013	0	830
Hydroelectric plant	1300	4	900[a]	0.407[a]	0	140[a]
Tidal turbine	1	1	490,000	0.000098	0.0013	7600
Roof PV system	0.003	6	1.7 billion	0.042[b]	0	265 million
Solar PV plant	300	14	40,000	0.097	0	6200
CSP plant	300	20	49,000	0.192	0	7600
Total		100		0.74	1.18	
Total new land				0.41[c]	0.59[c]	

[a] About 70% of the hydroelectric plants are already in place. See Jacobson (2009) for a discussion of apportioning the hydroelectric footprint area by use of the reservoir.
[b] The footprint area for rooftop solar PV does not represent an increase in land since the rooftops already exist and are not used for other purposes.
[c] Assumes 50% of the wind is over water, wave and tidal are in water, 70% of hydroelectric is already in place, and rooftop solar does not require new land.

minimize the effects of one turbine reducing energy to other turbines is ~1.17% of the global land area. The spacing can be used for agriculture, rangeland, open space, or can be open water. Whereas, wind turbines have foundations under the ground larger than their base on the ground, such underground foundation areas are not footprint, which is defined as the area of a device or plant touching the top surface of the soil, since such foundations are covered with dirt, allowing vegetation to grow and wildlife to flourish on top of them. The footprint area for wind also does not need to include temporary or unpaved dirt access roads, as most large-scale wind will go over areas such as the Great Plains and some desert regions, where photographs of several farms indicate unpaved access roads blend into the natural environment and are often overgrown by vegetation. Offshore wind does not require roads at all. In farmland locations, most access roads have dual purposes, serving agricultural fields as well as turbines. In cases where paved access roads are needed, 1 km^2 of land provides ~200 km (124 miles) of linear roadway 5 m wide, so access roads would not increase the footprint requirements of wind farms more than a small amount. The footprint area also does not include transmission, since the actual footprint area of a transmission tower is smaller than the footprint area of a wind turbine. This is because a transmission tower consists of four narrow metal support rods separated by distance, penetrating the soil to an underground foundation. Many photographs of transmission towers indicate more vegetation growing under the towers than around the towers since areas around that towers are often agricultural or otherwise used land whereas the area under the tower is vegetated soil. Since the land under transmission towers supports vegetation and wildlife, it is not considered footprint beyond the small area of the support axess roads.

For non-rooftop solar PV plus CSP, the areas required are considered here to be entirely footprint although technically a walking space, included here as footprint, is required between solar panels (Jacobson, 2009). Powering 34% of the world with non-rooftop solar PV plus CSP requires about one-quarter of the land area for footprint plus spacing as does powering 50% of the world with wind but a much larger footprint area alone than does wind (Table 4). The footprint area required for rooftop solar PV has already been developed, as rooftops already exist. As such, these areas do not require further increases in land requirements. Geothermal power requires a smaller footprint than does solar but a larger footprint than does wind per unit energy generated. The footprint area required for hydroelectric is large due to the large area required to store water in a reservoir, but 70% of the needed hydroelectric power for a WWS system is already in place.

Together, the entire WWS solution would require the equivalent of ~0.74% of the global land surface area for footprint and 1.18% for spacing (or 1.9% for footprint plus spacing). Up to 61% of the footprint plus spacing area could be over the ocean if all wind were placed over the ocean although a more likely scenario is that 30–60% of wind may ultimately be placed over the ocean given the strong wind speeds there (Fig. 1). If 50% of wind energy were over the ocean, and since wave and tidal are over the ocean, and if we consider that 70% of hydroelectric power is already in place and that rooftop solar does not require new land, the additional footprint and spacing areas required for all WWS power for all purposes worldwide would be only ~0.41% and ~0.59%, respectively, of all land worldwide (or 1.0% of all land for footprint plus spacing).

5. Material resources

In a global all-WWS-power system, the new technologies produced in the greatest abundance will be wind turbines, solar PVs, CSP systems, BEVs, and electrolytic-HFCVs. In this section, we examine whether any of these technologies use materials that either are scarce or else concentrated in a few countries and hence subject to price and supply manipulation.

5.1. Wind power

The primary materials needed for wind turbines include steel (for towers, nacelles, rotors, etc.), pre-stressed concrete (for towers), magnetic materials (for gearboxes), aluminum (nacelles), copper (nacelles), wood epoxy (rotor blades), glassfiber reinforced plastic (GRP) (for rotor blades), and carbon-filament reinforced plastic (CFRP) (for rotor blades). In the future, use of composites of GFRP, CFRP, and steel will likely increase.

The manufacture of four million 5 MW or larger wind turbines will require large amounts of bulk materials such as steel and concrete (USDOE, 2008a). However, there do not appear to be significant environmental or economic constraints on expanded production of these bulk materials. The major components of concrete – gravel, sand, and limestone – are widely abundant, and concrete can be recycled and re-used. The Earth does have a somewhat limited reserves of economically recoverable iron ore (on the order of 100–200 years at current production rates (USGS, 2009, p. 81)), but the steel used to make towers, nacelles, and rotors for wind turbines should be virtually 100% recyclable (for example, in the U.S. in 2007, 98% of steel construction beams and plates were recycled (USGS, 2009, p. 84)). The USDOE (2008a) concludes that the development of 20% wind energy by 2030 is not likely to be constrained by the availability of bulk materials for wind turbines.

For wind power, the most problematic materials may be rare earth elements (REEs) like neodymium (Nd) used in permanent magnets (PMs) in generators (Margonelli, 2009; Gorman, 2009; Lifton, 2009). In some wind-power development scenarios, demand for REEs might strain supplies or lead to dependence on potentially insecure supplies. (e.g., Margonelli, 2009; Hurst, 2010). One estimate suggests that current PM generators in large wind turbines use 0.2 kg Nd/kWh, or one-third the 0.6 kg/kWh of an Nd-based permanent magnet (Hatch, 2009). Building the 19 million installed MW of wind power needed to power 50% of world energy in 2030 (Table 4) would require 3.8 million metric tonnes of Nd, or about 4.4 million metric tonnes of Nd oxide (based on Nd_2O_3), which would amount to approximately 100,000 metric tons of Nd oxide per year over a 40–50 year period. In 2008, the world produced 124,000 metric tonnes of rare-earth oxide equivalent, which included about 22,000 metric tonnes of Nd oxide (Table 5). Annual world production of Nd therefore would have to increase by a factor of more than five to accommodate the demand for Nd for production of PMs for wind-turbine generators for our global WWS scenario.

The global Nd reserve or resource base could support 122,000 metric tonnes of Nd oxide production per year (the amount needed for wind generators in our scenario, plus the amount needed to supply other demand in 2008) for at least 100 years, and perhaps for several hundred years, depending on whether one considers the known global economically available reserves or the more speculative potential global resource (Table 5). Thus, if Nd is to be used beyond a few hundred years, it will have to be recycled from magnet scrap, a possibility that has been demonstrated (Takeda et al., 2006; Horikawa et al., 2006), albeit at unknown cost.

However, even if the resource base and recycling could sustain high levels of Nd use indefinitely, it is not likely that actual global production will be able to increase by a factor of five for many years, because of political or environmental limitations on expanding supply (Lifton, 2009; Reisman, 2009). Therefore, it seems likely that a rapid global expansion of wind power will require many

Table 5
Rare earth oxide and neodymium oxide (in parentheses)[a] production, reserves, and resources worldwide (million metric tonnes of rare earth oxide).
Source: USGS (2009, p. 131).

Country	Mine production 2008	Reserves	Reserve Base	Resources
United States	0 (0.000)	13 (2.0)	14 (2.1)	n.r.
Australia	0 (0.000)	5.2 (0.9)	5.8 (1.0)	n.r.
China	0.120 (0.022)	27 (4.9)	89 (16.0)	n.r.
CIS	n.a.	19 (3.4)	21 (3.8)	n.r.
India	0.003 (0.001)	1.1 (0.2)	1.3 (0.2)	n.r.
Others	0.001 (0.000)	22 (4.0)	23 (4.1)	
World total	*0.124 (0.022)*	*88 (15.3)*	*150 (27.3)*	*"very large"*[b]

CIS = Commonwealth of Independent States. n.a. = not available. "Reserves" are "that part of the reserve base which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative" (USGS, 2009, p. 192). The "Reserve Base" comprises reserves (as defined above), plus marginally economic resources, plus currently sub-economic resources. "Resources" comprise the reserve base (as defined above) plus commodities that may be economically extractable in the future (USGS, 2009, p. 191).

[a] Assumes that the Nd oxide content of total rare earth oxides is 15% in the U.S. and 18% in China, Australia, and all other countries (based on Table 2 of Hedrick, 2009).

[b] The USGS (2009) writes that "undiscovered resources are thought to be very large relative to expected demand" (p. 131).

generators that do not use Nd (or other REE) PMs or a rapid transition into recycling. There are at least two kinds of alternatives:

(i) generators that perform at least as well as PM generators but don't have scarce REEs (e.g., switched-reluctance motors (Lovins and Howe, 1992)), new high-torque motors with inexpensive ferrite magnets, and possibly high-temperature super-conducting generators (Hatch, 2009);
(ii) generators that don't use REEs but have higher mass per unit of power than do PM generators (the greater mass will require greater structural support if the generator is in the tower).

Morcos (2009) presents the most cogent summary of the implications of any limitation in the supply of Nd for permanent magnets:

> A possible dwindling of the permanent magnet supply caused by the wind turbine market will be self-limiting for the following reasons: large electric generators can employ a wide variety of magnetic circuit topologies, such as surface permanent magnet, interior permanent magnet, wound field, switched reluctance, induction and combinations of any of the above. All of these designs employ large amounts of iron (typically in the form of silicon steel) and copper wire, but not all require permanent magnets. Electric generator manufacturers will pursue parallel design and development paths to hedge against raw material pricing, with certain designs making the best economic sense depending upon the pricing of copper, steel and permanent magnets. Considering the recent volatility of sintered NdFeB pricing, there will be a strong economic motivation to develop generator designs either avoiding permanent magnets or using ferrite magnets with much lower and more stable pricing than NdFeB.

5.2. Solar power

Solar PVs use amorphous silicon, polycrystalline silicon, microcrystalline silicon, cadmium telluride, copper indium selenide/sulfide, and other materials. According to a recent review of materials issues for terawatt-level development of photovoltaics, the power production of silicon PV technologies is limited not by crystalline silicon (because silicon is widely abundant) but by reserves of silver, which is used as an electrode (Feltrin and Freundlich, 2008). That review notes that "if the use of silver as top electrode can be reduced in the future, there are no other significant limitations for c-Si solar cells" with respect to reaching multi-terawatt production levels (Feltrin and Freundlich, 2008, p. 182).

For thin-film PVs, substituting ZnO electrodes for indium thin oxide allows multi-terawatt production, but thin-film technologies require much more surface area. The limited availability of tellurium (Te) and indium (In) reduces the prospects of cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) thin cells.

For multi-junction concentrator cells, the limiting material is germanium (Ge), but substitution of more abundant gallium (Ga) would allow terawatt expansion.

Wadia et al. (2009) estimate the annual electricity production that would be provided by each of 23 different PV technologies if either one year of total current global production or alternatively the total economic reserves (as estimated by the USGS) of the limiting material for each technology were used to make PVs. They also estimate the minimum \$/W cost of the materials for each of the 23 PV technologies. They conclude that there is a "major opportunity for fruitful new research and development based on low cost and commonly available materials" (Wadia et al., 2009, p. 2076), such as FeS_2, CuO, Cu_2S, and Zn_3P_2.

On the basis of this limited review, we conclude that the development of a large global PV system is not likely to be limited by the scarcity or cost of raw materials.

5.3. Electric vehicles

For electric vehicles there are three materials that are of most concern: rare-earth elements (REEs) for electric motors, lithium for lithium-ion batteries, and platinum for fuel cells. Some permanent-magnet ac motors, such as in the Toyota Prius hybrid electric vehicle (Toyota, 2010), can use significant amounts of REEs. For example, the motor in the Prius uses 0.2–1 kg of Nd or 3.6–16.7 kg/MW (Maximum EV, 2009; Gorman, 2009). The low estimate is based on the assumption that the Prius' permanent magnet motors are 55 kW, with NDFeB magnet containing 31% Nd by mass (Maximum EV, 2009). The high kg/MW estimate assumes 60 kW motors (Toyota, 2010). Although this is an order of magnitude less than is used in some wind-turbine generators (see discussion above), the total potential demand for Nd in a worldwide fleet of BEVs with permanent-magnet motors would still be large enough to be of concern. However, there are a number of electric motors that do not use REEs, and at least one of these, the switched reluctance motor, currently under development for electric vehicles (e.g., Goto et al., 2005), is economical, efficient, robust, and high-performing (Lovins and Howe, 1992). Given this, we do not expect that the scarcity of REEs will appreciably affect the development of electric vehicles.

Next we consider lithium and platinum supply issues. To see how lithium supply might affect the production and price of battery-electric vehicles, we examine global lithium supplies, lithium prices, and lithium use in batteries for electric vehicles. Table 6 shows the most recent estimates of lithium production, reserves, and resources from USGS (2009).

Note that Table 6 does not include the recently discovered, potentially large lithium reserves in Afghanistan (Risen, 2010). Roughly half of the global lithium reserve base known in 2009 is in one country, Bolivia, which has been called "the Saudi Arabia of lithium" (Friedman-Rudovsky, 2009). However, Bolivia does not yet have any economically recoverable reserves or lithium production infrastructure (Ritter, 2009; Wright, 2010), and to date has not produced any lithium (Table 6). About 75% of the world's known

Table 6
Lithium production, reserve,s and resources worldwide as of 2009 (metric tonnes). *Source*: USGS 2009.

Country	Mine production 2008	Reserves	Reserve Base	Resources
United States	n.r.	38,000	410,000	n.r.
Argentina	3200	n.r.	n.r.	n.r.
Australia	6900	170,000	220,000	n.r.
Bolivia	0	0	5,400,000[a]	n.r.
Chile	12,000	3,000,000	3,000,000	n.r.
China	3500	540,000	1,100,000	n.r.
World total	*27,400*	*4,100,000*	*11,000,000*	*> 13,000,000*

n.r. = not reported. For explanation of terms, see notes to Table 5.

[a] Wright (2010, p. 58) reports that the head of the Bolivian scientific committee charged with developing Bolivia's lithium resources estimates that there are about 100,000,000 metric tonnes of metallic lithium in Bolivia.

economically recoverable reserves are in Chile, which is also the world's leading producer (Table 6). Both Bolivia and Chile recognize the importance of lithium to battery and car makers, and are hoping to extract as much value from it as possible (Wright, 2010). This concentration of lithium in a few countries, combined with rapidly growing demand, could increase the price of lithium upon expanded BEV production. Currently, lithium carbonate (Li_2CO_3) costs ~\$6–7/kg, and lithium hydroxide (LiOH), ~\$10/kg (Jaskula, 2008), which correspond to about \$35/kg Li. Lithium is ~1–2% of the mass of a lithium-ion battery (Gaines and Nelson, 2009; Wilburn, 2009, Table A-9); in a pure BEV with a relatively long range (about 100 miles), the battery might contain on the order of 10 kg of lithium (Gaines and Nelson, 2009). At current prices this adds ~\$350 to the manufacturing cost of a vehicle battery, but if lithium prices were to double or triple, the lithium raw material cost could approach \$1000, which would increase vehicle costs further.

At 10 kg per vehicle, the production of 26 million EVs per year – more than half of the 48 million passenger cars produced in the world in 2009 (OICA, 2010) – would require 260,000 metric tonnes-Li per year, which in the absence of recycling lithium batteries (which currently is negligible) would exhaust the current reserve base (Table 6) in less than 50 years. If one considers an even larger EV share of a growing, future world car market, and includes other demands for lithium, it is likely that the current reserve base would be exhausted in less than 20 years, in the absence of recycling. This is the conclusion of the recent analysis by Meridian International Research (2008).

However, the world will not consume lithium reserves in an uncontrolled manner until, one day, the supply of lithium is exhausted. As demand grows the price will rise and this will spur the hunt for new sources of lithium, most likely from recycling. Another potential source of lithium is the oceans, which contain 240 million tonnes, far more than all the known land reserves. However, currently the cost of extracting such lithium is high and energy intensive, so alternatives are strongly preferred. According to an expert, recycling lithium currently is more expensive than is mining virgin material (Ritter, 2009), but as the price of lithium rises, at some point recycling will become economical. The economics of recycling depend in part on the extent to which batteries are made with recyclability in mind, an issue that the major industries already are aware of: according to a recent report, "lithium mining companies, battery producers, and automakers have been working together to thoroughly analyze lithium availability and future recyclability before adopting new lithium-ion chemistries" (Ritter, 2009, p. 5). Gaines and Nelson (2010) discuss recycling processes for lithium-ion batteries, and write that "recovery of battery-grade material has been demonstrated" (p. 7).

Ultimately, then, the issue of how the supply of lithium affects the viability of lithium-ion-battery EVs in an all-WWS world boils down to the price of lithium with sustainable recycling. As noted above, it does make some difference to EV economics if that price is \$35/kg-Li or \$100/kg-Li.

Finally we consider the use of platinum in fuel cells. The production of millions of hydrogen fuel cell vehicles (HFCVs) would increase demand for Pt substantially. Indeed, the production of 20 million 50 kW HFCVs annually might require on the order of 250,000 kg of Pt—more than the total current world annual production of Pt (Yang, 2009; USGS, 2009, p. 123). How long this output can be sustained, and at what platinum prices, depends on several factors: (1) the technological, economic, and institutional ability of the major supply countries to respond to changes in demand; (2) the ratio of recoverable reserves to total production; (3) improvements in technology that reduce the cost of recovery; and (4) the cost of recycling as a function of quantity recycled.

Regarding the first factor, it does not seem likely that the current production problems in South Africa, mentioned by Yang (2009), will be permanent. Rather, it seems reasonable to assume that in the long run, output can be increased in response to large changes in demand and price. In support of this, the U.K. Department of Transport (UKDOT, 2006) cites a study that concludes that "production in South Africa could be expanded at a rate of 5% per year for at least another 50 years". TIAX (2030) finds that "the platinum industry has the potential to meet a scenario where FCVs achieve 50% market penetration by 2050, while an 80% scenario could exceed the expansion capabilities of the industry" (p. 7).

Regarding the second factor, Spiegel (2004) writes that the International Platinum Association concludes that "there are sufficient available reserves to increase supplies by up to 5–6% per year for the next 50 years," (p. 364), but does not indicate what the impact on prices might be. Gordon et al. (2006) estimate that 29 million kg of platinum-group metals are available for future use, and state that "geologists consider it unlikely that significant new platinum resources will be found" (p. 1213). This will sustain annual production of at least 20 million HFCVs, plus production of conventional catalyst-equipped vehicles, plus all other current non-automotive uses, for less than 100 years, without any recycling.

Regarding the third factor, TIAX (2003) argues that in the long run the price of platinum is stable because the extra cost of recovering deeper and more diffuse reserves is balanced by technological improvements that reduce recovery costs. It is not clear, however, that this improvement can be expected to continue indefinitely. Thus, the prospects for very long term use of platinum, and the long-term price behavior of platinum, depend in large part on the prospects for recycling (TIAX, 2003).

According to an expert in the precious-metal recycling industry, the full cost of recycled platinum in a large-scale, international recycling system is likely to be much less than the cost of producing virgin platinum metal (Hagelüken, 2009). Consistent with this, UKDOT (2006) cites an analysis that indicates that platinum recycling will be economical even if platinum loadings on fuel-cell catalysts are greatly reduced from current levels. Thus, the more the recycling, the less the production of high-cost virgin material, and hence the lower the price of platinum, since the price will be equal to the long-run marginal cost of producing virgin metal. The effect of recycling on platinum price, therefore, depends on the *extent* of recycling.

The prospects for recycling are difficult to quantify, because they depend more on institutional and logistical factors than on technical factors. The current rate of recycling autocatalysts is between 10% and 25%, if expressed as the ratio {Pt recovered from catalysts in year X}:{Pt used in new catalysts in year X} (Carlson and

Thijssen, 2002; Hagelüken et al., 2009; Hagelüken, 2009), but is around 50% if expressed as the ratio {Pt recovered from catalysts in year X}:{Pt used in new catalysts in the year in which the currently recycled products were made} (Hagelüken, 2009 (also quoted in Ritter, 2009, p. 4)). This second ratio, representing the "dynamic recycling rate," is more meaningful because it is based on the lifecycle of a particular product (e.g., Schaik and Reuter, 2004). Technically, there appears to be ample room to increase dynamic recycling rates. Hagelüken et al. (2009) believe that "a progressive conversion of existing open loop recycling systems to more efficient closed loops…would more than double the recovery of PGMs from used autocatalysts by 2020" (p. 342). (Hagelüken et al. (2009) and UKDOT (2006) also note that emissions from recycling PGMs are significantly lower than emissions from mine production of PGMs.) Spiegel (2004) states that "technology exists to profitably recover 90% of the platinum from catalytic converters" (p. 360), and in his own analysis of the impact of HFCV platinum on world platinum production, he assumes that 98% of the Pt in HFCVs will be recoverable. Similarly, Hagelüken, 2009 asserts that the technology is available to recover more than 90% of the platinum from fuel cells, although he believes that 98% recovery will be difficult to achieve. Finally, in their separate analyses of the impact of the introduction of hydrogen HFCVs on platinum supply and prices, UKDOT (2006) and TIAX (2003) assume that 95% of the platinum in fuel cells will be recovered and recycled. (UKDOT (2006) cites two sources, one of them a catalyst manufacturer, in support of its assumption.)

It seems likely that a 90%+ recycling rate will keep platinum prices lower than will a 50% recycling rate. The main barriers to achieving a 90%+ recycling rate are institutional rather than technical or economic: a global recycling system requires international agreement on standards, protocols, infrastructure, management, and enforcement (Hagelüken, 2009). We cannot predict when and to what extent a successful system will be developed.

Nevertheless, it seems reasonable to assume that enough platinum will be recycled to supply a large and continuous fuel-cell vehicle market with only moderate increases in the price of platinum, until new, less costly, more abundant catalysts or fuel cell technologies are found. Indeed, catalysts based on inexpensive, abundant non-platinum materials may be available soon (e.g., Lefèvre et al., 2009). Preliminary work by Sun et al. (2010) supports this conclusion. They developed an integrated model of HFCV production, platinum loading per HFCV (a function of HFCV production), platinum demand (a function of HFCV production, platinum loading, and other factors), and platinum prices (a function of platinum demand and recycling), and found that in a scenario in which HFCV production was increased to 40% of new LDV output globally in the year 2050, the average platinum cost per HFCV was $400, or about 10% of the cost of the fuel-cell system.

6. Summary of technical findings and conclusions

This is Part I of a study to examine the feasibility of providing all energy for all purposes (electric power, transportation, heating/cooling, etc.) worldwide from wind, water, and the sun (WWS). The main technical findings of this analysis are as follows:

Converting to a WWS energy infrastructure will reduce 2030 world power demand by 30%, primarily due to the efficiency of electricity compared with internal combustion. The amount of wind power plus solar power available in likely developable locations over land outside of Antarctica worldwide to power the world for all purposes exceeds projected world power demand by more than an order of magnitude.

One scenario for powering the world with a WWS system includes 3.8 million 5 MW wind turbines (supplying 50% of projected total global power demand in 2030), 49,000 300 MW CSP power plants (supplying 20% of demand), 40,000 solar PV power plants (14%), 1.7 3 kW rooftop PV systems (6%), 5350 100 MW geothermal power plants (4%), 900 1300 MW hydroelectric power plants, of which 70% are already in place (4%), 720,000 0.75 MW wave devices (1%), and 490,000 1 MW tidal turbines (1%).

The equivalent footprint area on the ground for the sum of WWS devices needed to power the world is ~0.74% of global land area; the spacing area is ~1.16% of global land area. Spacing area can be used for multiple purposes, including agriculture, ranching, and open space. However, if one-half of the wind devices are placed over water, if we consider wave and tidal devices are in water, and if we consider that 70% of hydroelectric is already developed and rooftop solar areas are already developed, the additional footprint and spacing of devices on land required are only ~0.41% and ~0.59% of the world land area, respectively.

The development of WWS power systems is not likely to be constrained by the availability of bulk materials, such as steel and concrete. In a global WWS system, some of the rarer materials, such as neodymium (in electric motors and generators), platinum (in fuel cells), and lithium (in batteries), will have to be recycled or eventually replaced with less-scarce materials unless additional resources are located. The cost of recycling or replacing neodymium or platinum is not likely to affect noticeably the economics of WWS systems, but the cost of large-scale recycling of lithium batteries is unknown.

In Part II of this study (Delucchi and Jacobson, this issue), we examine reliability, system and transmission costs, and policies needed for a worldwide WWS infrastructure.

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Appendix A

A.1. The economics of nuclear power

The economics of nuclear power are discussed in Kessides (2010), Grubler (2010), Joskow and Parsons (2009), Feiveson (2009), Koomey and Hultman (2007), Hultman et al. (2007), Hultman and Koomey (2007), Harding (2007), and Deutch et al. (2003, 2009). Kessides (2010) and Joskow and Parsons (2009) discuss at length the issues that affect the economics of nuclear power. Feiveson (2009) reviews recent escalation in capital costs. Grubler (2010) argues that the real costs of nuclear power can increase with an expansion of capacity (and in fact did increase in France) because of ever-increasing complexity in the design, construction, operation, management, and regulatory oversight of nuclear systems. Koomey and Hultman (2007) estimate that the total levelized busbar costs of 99 US reactors, including capital costs amortized at 6%/year, range from $0.03/kWh to $0.14/kWh (2004 USD), with the 50% percentile falling between $0.05/kWh and $0.06/kWh. Hultman et al. (2007) argue that costs at the upper end of the $0.03–0.14/kWh range are driven in part by unanticipated factors, and Hultman and Koomey (2007) argue that the possibility of such "cost surprises" should be incorporated formally into cost estimates for nuclear power. Koomey and Hultman (2007) argue that standardization of design, improvements in construction management, computer-assisted design, and other factors might tend to drive costs down, but that the special conditions that attend each nuclear job site, and the possibility of cost "surprises," tend to drive costs up. Deutch et al. (2003) estimate that the real levelized cost of nuclear power using an "open" or "once-through" fuel cycle (in which spent fuel is treated as waste, rather than recycled back to the reactor) ranges from \$0.04 to \$0.08/kWh (2002 USD) (with an effective interest rate of 11.5%), depending on assumptions regarding the capacity factor, the plant lifetime, construction costs, and construction time. Deutch et al. (2009) and Du and Parsons (2009) estimate that since the Deutch et al. (2003) report, construction costs have escalated substantially, resulting in a doubling of capital costs and an increase in the estimated median levelized cost from \$0.067/kWh in the 2003 study (2002 USD) to \$0.084/kWh in the 2009 update (2007 USD) (see also Joskow and Parsons, 2009). Harding (2007) estimates even higher levelized costs of \$0.09–0.12/kWh (2007 USD).

In summary, the costs of nuclear power are estimated to cover a very wide range, depending on a number of variables that are difficult to project: the costs of new, untested designs; construction times; interest rates; the impact of unforeseen events; regulatory requirements; the potential for economies of scale; site- and job-specific design and construction requirements; the availability of specialty labor and materials; bottlenecks in the supply chains; the potential for standardization; and so on.

A.2. Notes to Table 2

A.2.1. TW power in 2030 (fossil-fuel case)

This is the projected total world and total U.S. power for all energy end uses in the year 2030, in the conventional or business-as-usual scenario relying primarily on fossil fuels. The projections are from EIA (2008a); we converted from BTUs per year to Watts. The breakdown here is by type of energy in end use; thus, "renewables" here refers, for example, to end-use combustion of biomass, such as wood used for heating.

A.2.2. Electrified fraction

This is the fraction of energy service demand in each sector that can be satisfied feasibly by direct electric power. For example, gas water heating and space heating can readily be converted to air- and ground-source heat-pump water heaters and air heaters and electric resistance heaters. Liquid-fuel internal-combustion-engine vehicles can be replaced by battery electric vehicles. Indeed, direct electricity can, technically, provide almost any energy service that fuel combustion can, with the likely exception of transportation by air. However, in other cases, even if it is technically feasible, it may be relatively expensive or difficult for electricity to provide exactly the same service that fuel combustion does: for example, some cooking and heating applications where a flame is preferred, some large-scale direct uses of process heat, some applications of combined heat and power production, and some forms of heavy freight transportation. As explained below, we assume that energy services that are *not* electrified are provided by combustion of electrolytic hydrogen. Our assumptions regarding the directly electrified fraction in each sector are as follows:

A.2.3. Residential sector

We assume that 5% of fuel use for space heating and 20% of fuel use for "appliances" (mainly cooking) are *not* electrified, and then use the data from Table 2.5 of EIA (2008b) to calculate a weighted-average electrifiable fraction by type of fuel. We assume that renewables are mainly fuelwood, which will not be replaced with electricity. We assume that the estimates calculated on the basis of U.S. data apply to the world.

A.2.4. Commercial sector

We assume that the fraction of energy-end use that can be electrified is slightly less than we estimated for the residential sector, except in the case of renewables.

A.2.5. Industrial sector

We assume that 50% of direct-process heat end use, 50% of cogeneration and combined heat-and-power end use, and 25% of conventional boiler fuel use are *not* electrified, and then use data on manufacturing consumption of energy in the U.S. (Table 2.3 of EIA (2008b)) to calculate a weighted-average electrified fraction by type of fuel. We assume that the estimates calculated on the basis of U.S. data apply to the world.

A.2.6. Transport sector

We assume that 5% of motor-gasoline use, 30% of highway diesel-fuel use, 50% of off-road diesel fuel use, 100% of military fuel use, 20% of train fuel use, and 100% of airplane and ship fuel use are *not* electrified. We use data on transport energy consumption from the IEA (2008, p. 464, 508), data on transport fuel use in the U.S. (EIA, 2008b, Table 5.14c), and data on diesel fuel use in the U.S. (EIA, 2008b, Table 5.15) to estimate a weighted-average electrified fraction by type of fuel. We assume that estimates calculated on the basis of U.S. data apply to the world.

A.2.7. Non-electrified energy services

We assume that the remaining (non-electrified) energy service demands are met by hydrogen derived from electrolysis of water using WWS power. For analytical simplicity we assume that WWS power is delivered to the site of hydrogen use or refueling and used there to produce hydrogen electrolytically. (This is a useful simplification because it obviates the need to analyze a hydrogen transmission system.) We assume that in all sectors *except* transportation (e.g., in many industrial processes) the electrolytically produced hydrogen is burned directly to provide heat. In the transportation sector except aviation, we assume that hydrogen is compressed and then used in a fuel cell.

For aviation, we assume that hydrogen is liquefied and burned in jet engines. Coenen (2009), Nojoumi et al. (2009), Janic (2008), Maniaci (2006), Mital et al. (2006), Corchero and Montañes (2005), Koroneos et al. (2005), and Westenberger (2003) discuss various aspects of liquid-hydrogen-powered aircraft. Westenberger (2003), reporting on a European analysis of liquid-hydrogen aircraft systems (the CRYOPLANE project), concludes that hydrogen is a "suitable alternative fuel for future aviation" (p. 2), and could be implemented within 15–20 years (of 2003) with continued research and development of engines, materials, storage, and other components. Corchero and Montañes (2005) also discuss the CRYOPLANE project and conclude that "evolving a conventional engine from burning kerosene to burning hydrogen, without implementing large-scale hardware changes, does not seem to be an insurmountable task" (p. 42). Whereas, liquefied hydrogen aircraft would require about four times more volume to store their fuel, they would require three times less mass, since hydrogen is one-twelfth the density of jet fuel. Coenen (2009) asserts that "LH2 fueled aircraft are lighter, cleaner, quieter, safer, more efficient and have greater payload and range for equivalent weight of Jet A fuel," and that "there are no critical technical barriers to LH2 air transport" (p. 8452). Koroneos et al. (2005) perform a lifecycle assessment of the environmental impacts of jet fuel and hydrogen made from various feedstocks, and find that hydrogen made from water and wind power has the lowest impacts across all dimensions. For a discussion of liquid jet fuels made from biomass, see Hileman et al. (2009).

Thus, in transportation, all vehicles, ships, trains, and planes are either battery-powered or hydrogen powered. In this way, WWS power meets all energy needs, either directly as electricity or indirectly via electrolytic hydrogen.

A.2.8. End-use energy/work w.r.t. to fossil fuel

This is the ratio of BTUs-electric/unit-work to BTUs-fossil-fuel/unit-work. For example, it is the ratio of BTUs of electricity (at 3412 BTUs/kWh) input to an electric vehicle from the outlet, per mile of travel provided, to BTUs of gasoline input to a conventional vehicle from the pump, per mile of travel provided. In the case of electrified end uses, BTUs-electric are measured at the point of end use, and do not include any upstream or "indirect" electricity uses. In the case of electrolytic hydrogen (eH_2), BTUs-electric are measured at the input to the electrolyzer, which for simplicity is assumed to be at the site of end use, and again do not include any upstream or indirect electricity uses such as for hydrogen compression. (We treat compression and liquefaction separately, in the "upstream factor" column.) Thus, the figures shown for eH_2 include losses during electrolysis. Our estimates are based on results or assumptions from the *Advanced Vehicle Cost and Energy Use Model* (AVCEM) (Delucchi, 2005), the *Lifecycle Emissions Model* (LEM) (Delucchi, 2003), and other sources, as listed in Table A1.

A.2.9. Upstream factor

The upstream factor accounts for changes, in a WWS world compared with the base-case fossil-fuel world, in sectoral energy use in activities that are "upstream" of final end use by consumers. We first discuss these changes qualitatively, and then provide quantitative estimates of the changes in upstream fuel processing activities, which we believe are the largest of the upstream changes.

In a WWS world some of the energy-generation technologies (such as wind turbines), forms of energy (such as compressed hydrogen), and energy-use technologies (such as electric vehicles) will be different from those in a conventional fossil-fuel world. These differences will give rise to differences in energy use in the sectors that manufacture energy technologies and process energy. Qualitatively these differences are described in Table A2.

Table 2 has upstream adjustment factors for fuel use in the industrial sector and liquid fuel use in the transportation sector. The factors shown in Table 2 for the industrial sector account for the elimination of energy use in petroleum refining. The factor shown for liquid fuel in transportation accounts for electricity use for hydrogen compression or liquefaction. Our estimation of these factors is based on the data in Table A1.

Although 5–10% of the volumetric output of refineries is non-fuel product such as lubricants, petrochemical feedstocks, road asphalt, and petroleum coke (EIA, 2010), these products require much less than 5–10% of refinery energy, because refinery energy is used disproportionately to produce highly refined transportation fuels (Delucchi, 2003). Moreover, some of these non-fuel products would be eliminated in a WWS world (e.g., some kinds of lubricants), and some could be replaced at very low energy cost, for example, by recycling. For these reasons, we do not attempt to estimate the very small amount of refinery energy (probably on the order of 2%) that still would be required in a WWS world.

A.2.10. EHCM factor

EHCM stands for "electricity and hydrogen conservation measure." This is the ratio of demand for end-use energy after EHCMs have been instituted to the demand for end-use energy before the EHCMs. Demand-side energy-conservation measures include improving the energy-out/energy-in efficiency of end uses (e.g., with more efficient vehicles, more efficient lighting, better insulation in homes, and the use of heat-exchange and filtration systems), directing demand to low-energy-use modes (e.g., using public transit or telecommuting in place of driving), large-scale planning to reduce overall energy demand without compromising economic activity or comfort (e.g., designing cities to facilitate greater use of non-motorized transport and to have better matching of origins and destinations (thereby reducing the need for travel)), and designing buildings to use solar energy directly (e.g., with more daylighting, solar hot water heating, and improved passive solar heating in winter and cooling in summer). We assume that EHCMs can achieve modest reductions in energy demand, on the order of 5–15% in most cases.

A.2.11. TW power in 2030 (WWS case)

These are the world and the U.S. power in the year 2030 when wind, water, and solar power provide *all* energy services, and thus replace 100% of fossil-fuel use and biomass combustion. It is calculated from the other values in the table.

Table A1
Parameters values used to derive results in Table 2.

Value	Parameter	*Data source*
0.80	Efficiency of fossil-fuel heating (BTUs-work/BTUs-input-energy)	*LEM* (Delucchi, 2003)
0.97	Efficiency of electric resistance heating (BTUs-work/BTUs-power)	*LEM* (Delucchi, 2003)
0.80	Efficiency of hydrogen heating (BTUs-work/BTUs-input-energy)	*Assume same as fossil fuel*
0.70	Efficiency of electrolytic hydrogen production on site (BTUs-H_2/BTUs-electricity, higher heating value)	*AVCEM, LEM* (Delucchi, 2003, 2005; Aguado et al., 2009, *assume 75%*)
1.10	Work/energy ratio of hydrogen combustion in engines (mainly jet engines) relative to ratio for petroleum fuel	*LH2 in vehicles is more efficient than gasoline*
0.15	Of total liquid fuel use in transportation, the fraction that is replaced with liquefied H_2 rather than compressed H_2, on an energy basis	*Assume LH2 used by airplanes and some ships* (EIA, 2008b, Table 5.14c)
5.30	Ratio of mi/BTU for EVs to mi/BTU ICEVs	*AVCEM* (Delucchi, 2005)
2.70	Ratio of mi/BTU for HFCVs to mi/BTU ICEVs	*AVCEM* (Delucchi, 2005)
1.12	Multiplier for electricity requirements of H_2 compression for transportation (10,000 psi) (BTUs-electricity plus BTUs-H_2/BTU-H_2)	*AVCEM* (Delucchi, 2005)
1.32	Multiplier for electricity requirements of H_2 liquefaction for transportation, mainly air transport (includes boil-off losses) (BTUs-electricity plus BTUs-H_2/BTU-H_2)	*AVCEM* (Delucchi, 2005)
0.28	Petroleum energy in oil refining as a fraction of total petroleum use in industrial sector	*Projections for the U.S. for the year 2030* (EIA, 2009, Table 6)
0.18	NG energy in oil refining as a fraction of total NG use in industrial sector	*Projections for the U.S. for the year 2030* (EIA, 2009, Table 6)
0.27	Coal energy in oil refining as a fraction of total coal use in industrial sector	*Projections for the U.S. for the year 2030* (EIA, 2009, Table 6)
0.07	Electricity in oil refining as a fraction of total electricity use in industrial sector	*Projections for the U.S. for the year 2030* (EIA, 2009, Table 6)

Table A2
Qualitative differences between a fossil-fuel and a WWS world.

Sector	Fossil-fuel world	WWS world	Difference	Our treatment
Mining—oil, gas, and coal	Energy use in this sector typically is 1–4% of final fuel energy (Delucchi, 2003).	Energy use for mining for non-fuel products only.	Small reduction in energy use in a WWS world.	Not estimated.
Mining—other metals and minerals	Energy use in mining of metals and minerals for the production of power plants, motors, engines, vehicles, equipment, etc.; probably very small fraction of total energy use.	Energy use in mining of metals and minerals for the production of power plants, motors, engines, vehicles, equipment, etc. Because the types of equipment (etc.) produced will be different than in the fossil-fuel world, mining energy use will be different.	A WWS world will require more bulk materials (e.g., steel, concrete, etc.) per unit of power output than does a fossil-fuel world, and hence probably will require more energy in mining raw materials. This increase in energy use likely is small.	Not estimated.
Manufacturing—materials production and assembly for energy generation- and use-technologies	Energy use to make and assemble finished materials for power plants, motors, engines, vehicles, equipment, etc. For reference, direct and indirect energy in the manufacture of motor vehicles is 5–15% of the lifetime fuel energy (Delucchi, 2003).	Energy use to make and assemble finished materials for power plants, motors, engines, vehicles, equipment, etc. Because the types of equipment (etc.) produced will be different than in the fossil-fuel world, manufacturing energy use will be different.	To the extent that WWS technologies have greater mass per unit of power output (e.g., battery-electric vehicles versus gasoline vehicles), the manufacturing energy use will be greater.	Not estimated.
Manufacturing—materials production and assembly for energy delivery infrastructure	Energy use to make pipelines, tankers, trucks, trains, and power lines that carry energy, energy feedstocks, vehicles, and materials for the energy system.	Energy use to make pipelines, tankers, trucks, trains, and power lines that carry energy, energy feedstocks, vehicles, and materials for the energy system.	A WWS world will not have pipelines, tankers, trucks, or trains delivering fuel or fuel feedstocks, but will have more power lines, on balance, small reduction in energy use in WWS world?	Not estimated.
Manufacturing—fuel process	Petroleum refining and natural-gas processing.	Compression and liquefaction of hydrogen.	Significant net energy reduction in WWS world.	Estimated; see Table 2 and Section A.2.9.

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