Evaluating the Feasibility of a Large-Scale Wind, Water, and Sun Energy Infrastructure

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Climate change, air pollution, water pollution, and increasingly insecure and unreliable energy supplies are among the greatest environmental and economic challenges of our time. Addressing these challenges will require major changes to the ways we generate and use energy. With this in mind, scientists, policy analysts, entrepreneurs, and others have proposed large-scale projects to transform the global energy system from one that relies primarily on fossil fuels to one that uses clean, abundant, widespread renewable energy resources. Here, we analyze the feasibility associated with providing all our energy for all purposes from wind, water, and the sun (WWS), which we are the most promising renewable resources. We first describe the more prominent renewable energy plans that have been proposed, and then discuss in some detail the characteristics of WWS technologies, the availability of WWS resources, supplies of critical materials, the reliability of the generation and transmission systems, and economic and political issues.

Renewable Energy Plans

Over the past decade, a number of scientists have proposed large-scale renewable energy plans. In 2001, a Stanford University study (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). A 2002 paper published in *Science* (Hoffert et al., 2002) suggested a portfolio of solutions for stabilizing atmospheric CO_2, including increasing the use renewable energy and nuclear energy, decarbonizing fossil fuels and sequestering carbon, and improving energy efficiency. A 2004 Princeton University study (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. In 2008, another Stanford study (Jacobson, 2009) 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 proliferation. The ranking, starting with the highest, was: wind power, concentrated solar, geothermal, tidal, solar photovoltaic, wave, and hydroelectric power, all of which are powered by wind, water, or sunlight (WWS). The 2008 Stanford study also found that the use of battery-electric vehicles (BEVs) and hydrogen fuel-cell vehicles (HFCVs) powered by the WWS options would largely eliminate pollution from the transportation sector, and that nuclear power, coal with carbon capture, corn ethanol, and cellulosic ethanol are all worse than the WWS options with respect to climate change, air pollution, land use, and water pollution. Jacobson (2009) 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, using BEVs where the utility controlled when the electricity was dispatched through smart meters, and storing electricity in hydrogen or solar-thermal storage media.

Finally, a recent analysis of the technical, geographical, and economic feasibility for solar energy to supply the energy needs of the U. S. concludes that "it is clearly feasible to replace the present fossil fuel energy infrastructure in the US with solar power and other renewables, and reduce CO_2 emissions to a level commensurate with the most aggressive climate-change goals" (Fthenakis et al., 2009, p. 397).

More well known to the public than the scientific studies, perhaps, are the "Repower America" plan of former Vice-President and recent 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 power and improving energy efficiency (www.wecansolveit.org/pages/al_gore_a_generational_challenge_to_repower_america/). In Gore's plan, solar PV, geothermal, and biomass electricity would grow only modestly, and nuclear power and hydroelectricity would not grow at all.

Mr. Pickens' plan is to obtain up to 22% of 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 (www.pickensplan.com/theplan/).

For all of these studies and plans, two key issues are: how feasible is a large-scale transformation of the world's energy systems, and how quickly can such a transformation be accomplished? We address these issues by examining the characteristics of the technologies, the availability of energy resources, supplies of critical materials, the reliability of the generation and transmission systems, and economic and socio-political factors. Here we do not evaluate the impacts of WWS systems on climate change, air pollution, energy use, or water use and water pollution because these impacts already have been thoroughly examined in the literature (e.g., Jacobson, 2009).

Of course, the large-scale transformation of the energy sector worldwide would not be the first large-scale project undertaken in U.S. or world history. During World War II, the U.S. transformed motor vehicle production facilities to produce over 300,000 aircraft, and the rest of the world was able to produce an additional 486,000 aircraft (http://www.taphilo.com/history/WWII/Production-Figures-WWII.shtml). In the U. S., production increased from about 2,000 units in 1939 to almost 100,000 units in 1944. In 1956, the U. S. began work on the Interstate Highway System, which now extends for 47,000 miles and is considered one of the largest public works project in history (http://en.wikipedia.org/wiki/Interstate_Highway_System). And the iconic Apollo Program, widely considered one of the greatest human accomplishments of all time, put a man on the moon in less than 10 years – the time frame of Mr. Gore's Repower America plan. Although these projects obviously differ in important economic, political, and technical ways from the project we discuss, they do suggest that the large scale of a complete transformation of the energy system is not, in itself, an insurmountable barrier.

Technologies

Because proposals like Mr. Gore's require that we begin replacing existing energy generation with clean renewable energy sources as soon as possible, we discuss only those technologies and policies that work or are close to working today, on a global scale, rather than those that may exist 20 or 30 years from now. (This means, for example, that we do not discuss the prospects for nuclear fusion.) 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 nearly zero emissions of greenhouse gases and air pollutants per unit of output, over the whole "lifecycle" of the system. Similarly, we consider technologies that have low impacts on wildlife, water pollution, and land, and do not have significant waste-disposal or terrorism risks associated with them. Previous work by one of us (Jacobson, 2009) indicates that wind (wind and wave power), water (geothermal, hydroelectric and tidal power), and sun (concentrated solar and solar photovoltaic power) power satisfy all of these criteria. All of these technologies can be deployed today, and most of them already have been deployed on at least small scales worldwide.

We do not consider any combustion sources (coal with carbon capture, corn ethanol, cellulosic ethanol, soy biodiesel, algae biodiesel, other biofuels, or natural gas) or nuclear energy (fission, breeder reactors, or fusion), because none of these technologies are likely to reduce GHG and air-pollutant emissions to near zero, and all have significant problems in terms of land use, resource availability, waste disposal, or the risk of terrorism. 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), because the method of producing ethanol has no impact on the tailpipe-emissions from ethanol combustion or the resulting urban air pollution. Further, nuclear energy results in up to 25 times more carbon emissions than wind energy, in part due to the emissions from uranium refining and transport and reactor construction and in part due to the longer time required to permit and construct a nuclear plant compared with a wind farm , resulting in greater emissions from the fossil-fuel electricity sector during this period (Koomey and Hultman, 2007; Sovacool, 2008; Jacobson, 2009). Moreover, historically the growth of nuclear energy has increased the ability of nations to refine uranium for nuclear weapons purposes, and a large-scale expansion of nuclear energy worldwide would exacerbate this. Breeder reactors, while producing less low-level radioactive waste than do conventional reactors, produce uranium closer to weapons grade. The use of carbon capture and sequestration (CCS) can reduce CO_2 emissions from the stacks of coal power plants by more than 90%, but it will *increase* emissions 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 than does a system without CCS (IPCC, 2005).

For these reasons, we focus on WWS technologies. We assume that WWS will supply electric power to the transportation and heating and cooking sectors – which traditionally have relied mainly on direct use of oil or gas rather than electricity – as well as to traditional electricity-consuming end uses such as lighting, cooling, manufacturing, motors, electronics, and telecommunications. Although we focus mainly on energy *supply,* we acknowledge the importance of demand-side energy conservation measures to reduce the requirements and impacts of energy supply. Demand-side energy-conservation measures includes 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). (For a general discussion of the potential to reduce energy use in transportation and buildings, see the American Physical Society [2008]).

Electricity-Generating Wind, Water, and Sun Technologies

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.

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.

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.

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).

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 six hours in one direction before switching directions for six hours, tidal turbines can provide a predictable energy source.

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.

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.

<u>Electric vehicles and electric heating</u>

Vehicle and heating technologies that must be deployed on a large scale to use WWS-power include battery-electric vehicles (BEVs), hydrogen fuel cell vehicles (HFCVs), electric hot water heaters, electric resistance heaters, and electric heat pumps, among others.

BEVs store electricity in batteries and draw power from the batteries to run an electric motor that drives the vehicle. So long as the ultimate electricity source is clean, the BEV system can reduce emissions significantly compared with an internal combustion engine vehicle (ICEV) run on a liquid fuel. Indeed, BEVs using WWS power would be completely zero-emission vehicles. Moreover, BEVs get about 5 times more work (in miles of travel) per unit of input energy than do ICEVs (mi/kWh-outlet versus mi/kWh-gasoline). BEVs have existed for decades in small levels of production, and 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 which 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). Several companies have prototype HFCVs, and California has about 200 HFCVs on the road (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 as clean as that produced by WWS-electrolysis.

Electric water heaters, resistance heaters and heat pumps are existing technologies used on a large scale already, although in most places they satisfy less of the final demand than do natural gas and even oil-fired heaters. The use of electricity for heating and cooking, like the use of electricity for transportation, is maximally beneficial when the electricity comes from WWS.

Energy Resources Needed and Available

The power required today to satisfy all end uses worldwide is about 12.5 trillion watts (TW) (Energy Information Administration, 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 U. S. Energy Information Administration (EIA) projects that in the year 2030, the world will require almost 17 TW of end-use power, and the U. S. almost 3 TW (Table 1). The EIA (2008a) also projects that the breakdown in terms of primary energy in 2030 will be similar to today's – 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 1 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 the notes to Table 1 (in Appendix A.1), we assume that most uses of fossil fuels for heat can be replaced by electric resistance heating, and that most uses of liquid fuels for transportation can be replaced by battery-electric vehicles. The remaining, non-electrified uses can be supplied by hydrogen, which we assume would be compressed or liquefied for use in the transportation sector (and used mainly with fuel cells, except in aviation), and combusted to provide heat directly in the residential, commercial, and industrial sectors. The hydrogen would be produced by using WWS power to split water; thus, directly or indirectly, WWS powers the world.

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

Table 1. Projected end-use power in 2030, by sector, U. S. and world, conventional fossil-fuel case and replacing 100% of fossil fuels and wood combustion with WWS.

	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.1

How do the energy requirements of a WWS world, shown in Table 1, compare with the availability of WWS power? Table 2 shows 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 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 three times over and solar, about 15-20 times over. The U.S. could theoretically replace 100% of its 2007 carbon-emitting pollution with 389,000-645,000 5 MW wind turbines. Globally, wind could theoretically replace all fossil-fuel carbon with about 2.2-3.6 million 5 MW turbines (assuming the use of new vehicle technologies, such as BEVs)

Table 2. Power available in energy resource worldwide if used in energy 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[h]	920 [i]	240[j]	000046[d]

[a] Fig. 1; 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 100 m (Fig. 1).
[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, 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 50 S and 50 N.
[j] Scaling solar PV resource with relative land area requirements from Jacobson (2009).

Figure 1 shows the world wind resources at 100 m, in the range of the height of modern wind turbines. Globally, ~1700 TW of wind energy are available over the worlds land plus ocean surfaces if all wind were used to power wind turbines (Table 2); however, the wind power over land in locations where the wind speed is 7 m/s or faster (the speed necessary for cost-competitive wind energy), is around 72-170 TW.

About half of this power is in locations that could practically be developed. Fast wind locations worldwide include in 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. In the U.S., wind from the Great Plains and offshore the East Coast could supply all the U.S. energy needs. Although offshore wind energy is more expensive than onshore wind energy, it has been deployed significantly in Europe.

Figure 1. Modeled map of the yearly-averaged world wind speed (m/s) at 100 m above sea level.

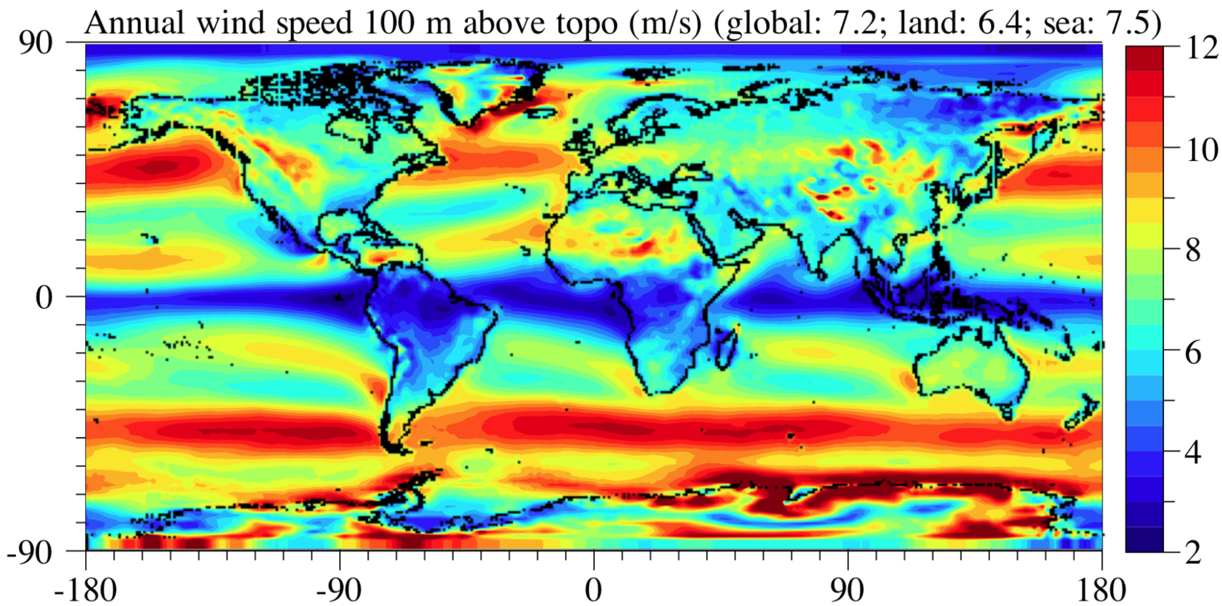
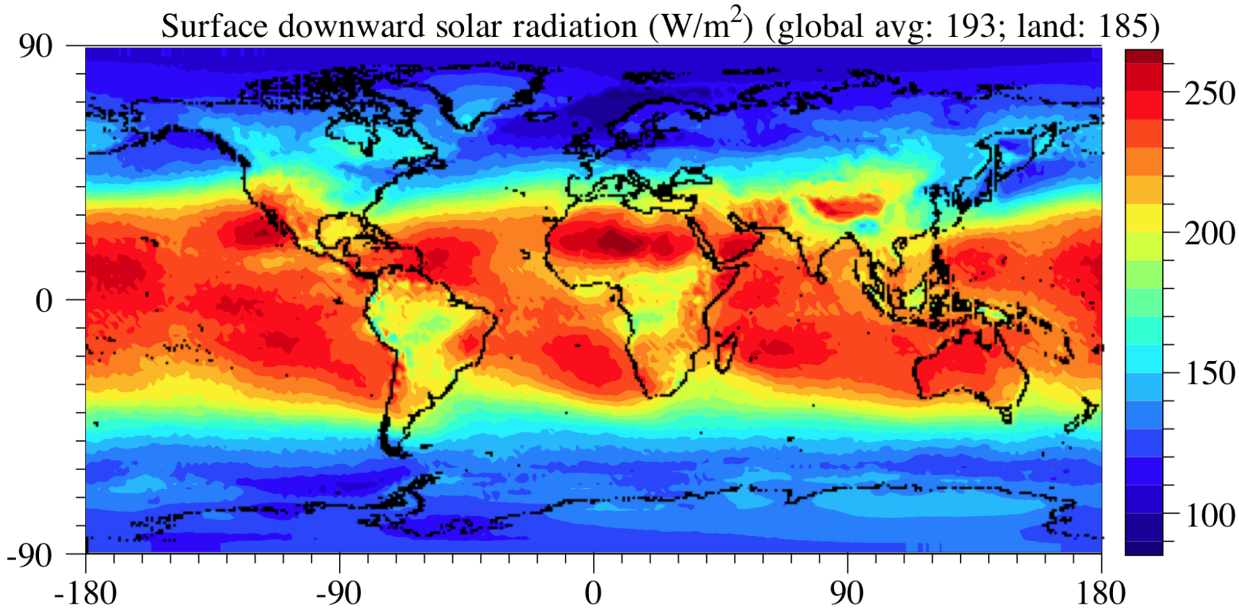


Figure 2 shows the global distribution of solar energy at the Earth's surface. Globally, 6500 TW of solar energy is available over the world's land plus ocean surfaces if all sunlight were used to power photovoltaics (Table 2); however, the deliverable solar power over land in locations where solar PV 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 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, CSP plants can require large amounts of water (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 2.

Figure 2. Modeled map of the yearly-averaged downward surface solar radiation reaching the surface (W/m^2).



The other kinds of WWS technologies have much less potential than do wind, CSP, and PV (Table 2). 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. And even though today hydroelectric power 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. However, existing and some new hydro will be valuable for filling in gaps in supply due to wind and solar power, in particular.

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

Number of Plants and Devices Required

How many WWS power plants or devices are required to power the world and U.S.? Table 3 provides an estimate for 2030, assuming a given fractionation of the demand (from Table 1) among technologies. Wind and solar together are assumed to comprise 90% of the future supply based on their relative abundances (Table 2). Although 4% is hydro, most of this amount (70%) is already in place. Solar PV is assumed to be divided 30% rooftop and 70% power plant. The table suggests 4 million 5-MW wind turbines (over land or water) and about 90,000 300-MW PV plus CSP power plants are needed. Already, about 0.8% of the wind is installed. The worldwide footprint on the ground (for the turbine tubular tower and base) for the 4 million wind turbines is only 48 km^2, whereas the spacing needed (which can be used for agriculture, rangeland or open space) is ~1% of the global land area. For non-rooftop solar PV plus CSP, powering 34% of the world requires about 1/3 of the land area as the spacing area required for wind.

Table 3. Number of WWS power plants or devices needed to power the world's and the U.S.'s total energy demand in 2030 (11.5 TW and 1.8 TW, respectively, from Table 1) assuming a given partitioning of the demand among plants or devices.

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	Number of plants or devices needed U.S.
Wind turbine	5	50	3.8 million	590,000
Wave device	0.75	1	720,000	110,000
Geothermal plant	100	4	5350	830
Hydroelectric plant	1300	4	900	140
Tidal turbine	1	1	490,000	7600
Roof PV system	0.003	6	1.7 billion	265 million
Solar PV plant	300	14	40,000	6200
CSP plant	300	20	49,000	000046

Material Resources

In a global all-WWS-power system, the key new technologies will be wind-power turbines, solar PVs, CSP systems, battery EVs, and fuel-cell EVs. 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.

<u>Wind power</u>. The primary materials needed for wind turbines include steel (for towers, nacelles, rotors), prestressed 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, there likely will be greater use of composites of GFRP, CFRP, and steel.

The manufacture of hundreds of thousands MW-size wind turbines will require very large amounts of bulk materials such as steel and concrete. However, there do not appear to be any 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 somewhat limited reserves of economically recoverable iron ore (on the order of 100 to 200 years at current production rates [U. S. Geological Survey, 2009, p. 81]), but the steel used to make towers, nacelles, and rotors for wind turbines should be 100% recyclable (for example, in the U. S. in

2007, 98% of steel construction beams and plates were recycled [U. S. Geological Survey (USGS), 2009, p. 84]). The U. S. Department of Energy (2008) 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; www.glgroup.com/News/Braking-Wind--Wheres-the-Neodymium-Going-To-Come-from--35041.html.). In some wind-power development scenarios, demand for REEs might strain supplies or lead to dependence on potentially insecure supplies. (In this respect, one analyst has raised the prospect of "trading a troubling dependence on Middle East oil for a risky dependence on Chinese neodymium" (Irving Mintzer, quoted in Margonelli, 2009). One expert estimates that current PM generators in large wind turbines use 200 kg of Nd per MW of power produced (http://nucleargreen.blogspot.com/2009/01/jack-liftons-research-on-mineral.html; www.terramagnetica.com/2009/08/03/how-does-using-permanent-magnets-make-wind-turbines-more-reliable/). To build the 19 million MW of wind power we assumed for the world in 2030 (Table 3) would require 3.8 million metric tonnes of Nd, or about 4.4 million metric tones of Nd oxide (based on Nd_2O_3; http://en.wikipedia.org/wiki/Neodymium), which would amount to approximately 100,000 metric tons of Nd oxide per year over a 40 to 50 year period. In 2008, the world produced 124,000 metric tones of rare-earth oxide equivalent, which included about 22,000 metric tones of Nd oxide (Table 4). 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.

Table 4. Rare earth oxide and neodymium oxide (in parentheses)[a] production, reserves and resources worldwide (million metric tones of rare earth oxide)

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]

Source: USGS (2009, p. 131). 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).

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 4). 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 (www.glgroup.com/News/Braking-Wind--Wheres-the-Neodymium-Going-To-Come-from--35041.html, http://agmetalminer.com/2009/09/03/china-and-rare-earth-metals-—-two-sides-to-every-story-part-one/, www.telegraph.co.uk/finance/comment/ambroseevans_pritchard/6082464/World-faces-hi-tech-crunch-as-China-eyes-ban-on-rare-metal-exports.html, http://irblog.blogs.com/rare_metal_blog/2009/08/blog-the-sky-is-not-falling-a-different-perspective-on-the-chinese-miit-report-on-rare-earths.html). Therefore, it seems likely that a rapid global expansion of wind power will have to use generators that do not have Nd (or other REE) PMs. There are at least three 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 [www.tradingmarkets.com/.site/news/Stock%20News/2559360/], and possibly high-temperature super-conducting generators [www.terramagnetica.com/2009/08/07/10-mw-and-beyond-are-superconductors-the-future-of-wind-energy/]);
ii) generators that don't have 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); and
iii) generators that have higher mass but are placed on the ground (this eliminates the need for extra structure to support the generator, but requires redesign of the whole turbine system).

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.

Solar power. Solar PVs use amorphous silicon, polycrystalline silicon, micro-crystalline 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 was used to make PVs. The 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.

Electric vehicles. For electric vehicles there are three materials that might be problematic: 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 (www.hybridsynergydrive.com/en/electric_motor.html), can use significant amounts of REEs: according to Gorman (2009), the motor in the Prius uses 1 kg of Nd, or 16-kg/MW (assuming that the Prius has a 60-kW motor [www.hybridsynergydrive.com/en/electric_motor.html]).[1] Although this is an order of magnitude less than is used some wind-turbine generators (see discussion above), the total potential demand for Nd in a worldwide fleet of EVs with permanent-magnet motors still would 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 5 shows the most recent estimates of lithium production, reserves, and resources from the U. S. Geological Survey (USGS) *Minerals Commodity Summaries* (USGS, 2009).

[1] Another expert estimates that the Prius' permanent magnet motors have 0.45 kg Nd per motor (www.magnetweb.com/Col04.htm).

Table 5. Lithium production, reserves and resources worldwide (metric tonnes)

Country	Mine production 2008	Reserves	Reserve Base	Resources
United States	n.r.	38,000	410,000	n.r.
Argentina	3,200	n.r.	n.r.	n.r.
Australia	6,900	170,000	220,000	n.r.
Bolivia	0	0	5,400,000	n.r.
Chile	12,000	3,000,000	3,000,000	n.r.
China	3,500	540,000	1,100,000	n.r.
World total	*27,400*	*4,100,000*	*11,000,000*	*> 13,000,000*

Source: USGS (2009). n.r. = not reported. For explanation of terms, see notes to Table 4.

Roughly half of the global lithium reserve base is in one country, Bolivia, which *Time* magazine has called "the Saudi Arabia of lithium" (www.time.com/time/world/article/0,8599,1872561,00.html). However, Bolivia does not yet have any economically recoverable reserves or lithium production infrastructure (Ritter, 2009), and to date has not produced any lithium (Table 5). About 3/4ths of the world's known economically recoverable reserves are in Chile, which is also the world's leading producer (Table 5). 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. This concentration of lithium in a few countries, combined with rapidly growing demand, could cause increases in the price of lithium. Currently, lithium carbonate (Li_2CO_3) sells for about $6-7/kg, and lithium hydroxide (LiOH) sells for about $10/kg (Jaskula, 2008), prices which correspond to about $35/kg-Li. Now, lithium is 1% to 2% of the mass of lithium-ion batteries (Gaines and Nelson, 2009; Wilburn, 2009, Table A-9); in a pure battery EV 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 amount of lithium would contribute $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 $1,000. This could have a significant impact on the cost of an electric vehicle.

At 10 kg per vehicle, the production of 26 million EVs per year – half of the total passenger-car production in the world in 2008 (http://oica.net/category/production-statistics/) – would require 260,000 metric tonnes of lithium per year, which in the absence of recycling lithium batteries (which currently is negligible) would exhaust the current reserve base (Table 5) 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).

Of course, the world is not going to consume lithium reserves in an uncontrolled manner until suddenly, one day, the supply of lithium is exhausted. As demand grows the price will rise and this will spur the hunt for other sources of lithium, most likely from recycling. According to an expert at the USGS, 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 which 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).

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. It is clear that the productions of millions of fuel cell vehicles (FCVs) would increase demand for Pt substantially. Indeed, the production of 20 million 50-kW FCVs 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 at least three 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, and 3) 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. It seems reasonable to assume that in the long run, output can be increased in response to large changes in demand and price.

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 FCVs, plus production of conventional catalyst-equipped vehicles, plus all other current non-automotive uses, for less than 100 years, without any recycling. 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.

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 (C. Hagelüken, Umicore, personal communication, 2009). Thus, the more 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 economical recycling are difficult to quantify. In 1998, only 10 metric tons of Pt were available from recycling automobile catalysts (USGS, 1999). Carlson and Thijssen

(2002) report that recycling of automotive catalysts is between only 10% and 20%, but they note that economic theory predicts that recycling will increase as demand increases. Similarly, Hagelüken et al. (2009) estimate that in Germany the amount of material recovered from recycling of platinum-group metals (PGMs) from automobile catalysts is 12% of gross demand for PGMs for automobile catalysts, but they 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).[2] (They also note that emissions from recycling PGMs are significantly lower than emissions from mine production of PGMs.) Spiegel (2004) states that the "technology exists to profitably recover 90% of the platinum from catalytic converters" (p. 360), and in his own analysis of the impact of FCV platinum on world platinum production (but not price), he assumes that 98% of the Pt in FCVs will be recoverable. On the other hand, Gordon et al. (2006) assume that only 45% of the Pt in FCVs will be recovered.

It seems likely that a 95% recycling rate will keep platinum prices significantly lower than will a 50% recycling rate. The main barriers to achieving a 95% recycling rate are institutional rather than technical or economic: a global recycling system requires international agreement on standards, protocols, infrastructure, management, and enforcement (C. Hagelüken, Umicore, personal communication, 2009). We cannot predict when and to what extent a successful system will be developed.

Nevertheless, we believe that enough platinum will be recycled to supply a large fuel-cell vehicle market and 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 materials may be available relatively soon: Lefèvre et al. (2009) report that a microporous carbon-supported iron-based catalyst was able to produce a current density equal to that of a platinum-based catalyst with 0.4 mg-pt/cm^2 at the cathode. Although the authors note that further work is needed to improve the stability and other aspects of iron-based catalysts, this research suggests a world-wide fuel-cell vehicle market will not have to rely on precious-metal catalysts indefinitely.

Reliability

A new WWS energy infrastructure must be able to provide energy on demand at least as reliably as does the current infrastructure. The main challenge for the current infrastructure is that electric power demand varies during the day and during the year, while most supply (coal, nuclear, and geothermal) is constant during the day, which means that there is a difference to be made up by peak- and gap-filling resources such as natural gas and hydropower. Another challenge to the current system is that extreme events and unplanned maintenance can shut down plants unexpectedly. For example, unplanned maintenance can shut down coal plants, extreme heat waves can cause cooling water to warm sufficiently to shut down nuclear plants, supply

[2] However, elsewhere, Hagelüken is quoted as saying that "50% of PGMs from automobile catalysts are recovered," (Ritter, 2009, p. 4).

disruptions can curtail the availability of natural gas, and droughts can reduce the availability of hydroelectricity.

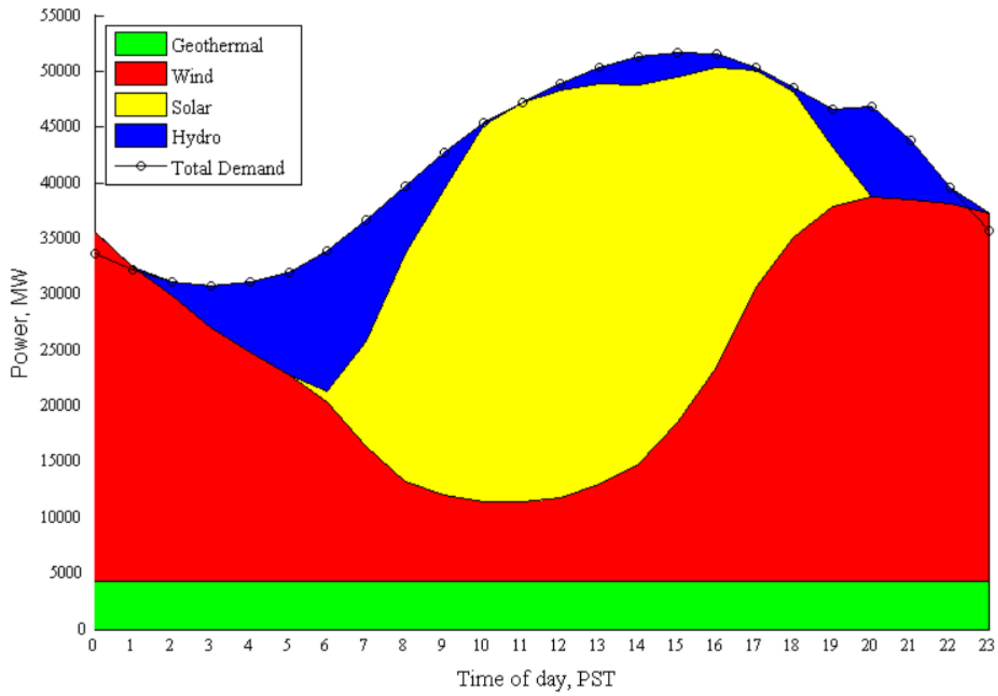
A WWS infrastructure offers new challenges but also new opportunities with respect to reliably meeting energy demands. On the positive side, WWS technologies generally suffer less downtime than current electric power technologies. For example, the average coal plant in the U.S. from 2000-2004 was down 6.5% of the year for unscheduled maintenance and 6.0% of the year for scheduled maintenance (North American Reliability Corporation, 2009), but modern wind turbines have a down time of only 0-2% over land and 0-5% over the ocean (Dong Energy, et al., 2006). Similarly, solar-PV panels have a downtime of around 0-2%. Moreover, there is an important difference between outages of centralized power plants (coal, nuclear, natural gas) and outages of distributed plants (wind, solar, wave): when individual solar panels or wind turbines are down, only a small fraction of electrical production is affected, whereas when a centralized plant is down, a large fraction of the grid is affected.

The main new challenge is that several WWS technologies (wind, wave, PV, and CSP) are variable when considered in isolation at one location: the wind does not always blow and the sun does not always shine. (Of course, other WWS technologies are not variable: tidal power is relatively reliable because of the predictability of the tides; geothermal energy supply is generally constant; and hydroelectric power can be turned on and off quickly and currently used to provide peaking and gap-filling power.) There are at least five ways to mitigate variability or its effects: (a) interconnect geographically-disperse naturally-variable energy sources (e.g., wind, solar, wave, tidal), (b) use a reliable energy source, such as hydroelectric power, to smooth out supply or match demand, (c) use smart meters to provide electric power to vehicles in such a way as to smooth out electricity supply, (d) store electric power for later use, and (e) forecast the weather to plan for energy supply needs better.

Interconnecting geographically-disperse wind, solar, or wave farms to a common transmission grid smoothes out electricity supply significantly. For wind, interconnection over regions as small as a few hundred kilometers apart can eliminate hours of zero power, accumulated over all wind farms. For example, in one study, when 13-19 geographically disperse wind sites in the Midwest, over a region 850 km x 850 km, were hypothetically interconnected, about 33% of yearly-averaged wind power was calculated to be usable at the same reliability as a coal-fired power plant. To improve the efficiency of variable electric power sources, an organized and interconnected transmission system is needed. Ideally, fast wind sites would be identified in advance and the farms would be developed simultaneously with an updated interconnected transmission system. The same concept applies to other variable electric power sources.

A second method of reducing the effect of intermittency of wind is to combine multiple WWS energy sources together, to reduce overall intermittency, and to use hydroelectric or geothermal power to fill in the gaps. This concept is illustrated for California in Figure 3.

Figure 3. Example of powering 100% of California's July electricity with load-matching renewables in 2020.



Notes: The renewables include wind (26,425 MW installed, 8443 MW generated), solar-PV without storage (39,828 MW installed, 12,436 MW generated), geothermal (4700 MW installed, 4324 MW generated), and hydroelectric (13,500 MW installed - the current installation, 9854 MW generated). Hydroelectric is used to fill in gaps, as it currently does in California. Other baseload sources are assumed to supply 20% of electricity. The top line is the monthly-averaged power demand estimated for July, 2020, from California Energy Commission data. January demand is much lower (peaking at 37,000 MW) and is met by higher wind production offsetting lower solar production. From Hoste et al. (2008).

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

A fourth method of dealing with variability is to store excess energy in batteries (e.g., for use in BEVs), hydrogen gas (e.g., for use in HFCVs), pumped hydroelectric power, compressed air (e.g., in underground caverns or turbine nacelles), flywheels, or a thermal storage medium (as is done with CSP). One calculation shows that the storage of electricity in car batteries, not only to power cars but also to provide a source of electricity back to the grid (vehicle-to-grid, or V2G), could stabilize wind power if 50% of U.S. electricity were powered by wind and 3% of vehicles were used to provide storage (Kempton and Tomic, 2005). The only disadvantage of storage for grid use rather than direct use is energy conversion losses in both directions rather than in one.

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

Economics

An important criterion in the evaluation of WWS systems is the full private cost of delivered power, including annualized total capital and land costs, operating and maintenance costs, storage costs, and transmission costs, per unit of energy delivered.[3] Table 6 presents estimates of current (2005 to 2010) and future (2020 and beyond) $/kWh costs of power generation and transmission for WWS systems, with average U. S. delivered electricity prices based on conventional (mostly fossil) generation (excluding electricity distribution) shown for comparison. Wind, hydroelectric, and geothermal systems already can cost less than typical fossil and nuclear generation, and in the future wind power is expected to be less costly than any other form of large-scale power generation. [4]

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[3] Electricity generation technologies sometimes are compared on the basis of the capital cost per kW of power capacity, but because this is neither a complete measure of the relevant costs nor a measure of the energy provided, it is not a useful basis for comparison. Appendix A.2 shows EIA (2009a, b) estimates of capital costs for various generating technologies, and then derives total amortized+operating costs per kWh from the capital costs and other parameters.

[4] Our calculation of generating costs by technology based on EIA estimates, shown in part 1 of Appendix A.2, results in higher $/kWh values for WWS technologies than the estimates in Table 6, when we use all of the EIA's parameter values. This is due mainly to the EIA's relatively high discount rate and relatively short amortization period, both of which increase the amortized capital costs, which dominate for the renewable technologies. However, when we use the a lower (but more typical) discount rate, a longer (but realistic) lifetime, and the EIA's own "falling cost" case values for WWS technologies, the resultant estimates of generating costs for wind, geothermal, hydro, and solar thermal are comparable to those in Table 6 (part 2 of Appendix A.2).

Table 6. Approximate fully annualized generation and transmission costs for WWS power

Energy Technology	**Annualized cost (~2007 $/kWh-delivered)**	
	Present (2005-2010)	*Future (2020+)*
Wind [a]	$0.04 to $0.07	< $0.04
Wave [b]	≥ $0.11	$0.04
Geothermal [c]	$0.04 to $0.07	$0.04 to $0.07
Hydroelectric [d]	$0.04	$0.04
CSP [e]	$0.11 to $0.15	$0.08
Solar PV [f]	> $0.20	$0.10
Conventional (mainly fossil) generation in U. S. [g]	$0.07	$0.08

[a] Present costs are from Sovacool and Watts (2009), Schilling and Esmundo (2009), and Berry (2009); we have added $0.01 for electricity transmission (EIA, 2009a, Table A8 estimates $0.009/kWh). Future costs are projections from Schilling and Esmundo (2009).

[a] Bedard et al. (2005) estimate a levelized production cost of about $0.10/kWh for "the first commercial commercial scale wave plant" (we have added $0.01/kWh for transmission). They then project cost as a function of installed generating capacity using a learning-curve model and estimate levelized production cost comparable to that for wind power.

[c] Present costs are from Sovacool and Watts (2009) and Schilling and Esmundo (2009); we have added $0.01 for electricity transmission. For the future, we assume that some trends increase costs (e.g., drilling deeper wells), but that other trends decrease costs (e.g, developing more cost-effective technology), with the overall result that future costs are the same as present costs.

[d] Present costs are from Sovacool and Watts (2009); we have added $0.01 for electricity transmission. We assume that future costs are the same as present costs.

[e] Present costs are from Sovacool and Watts (2009) and Schilling and Esmundo (2009); we have added $0.01 for electricity transmission. Future costs are from Fthenakis et al. (2009), for a baseload plant, and include long-distance high-voltage dc transmission.

[f] Present costs are from Fthenakis et al. (2009), Mondol et al. (2009), Sovacool and Watts (2009), and Schilling and Esmundo (2009). Future costs are from Fthenakis et al. (2009) and include compressed air energy storage, which costs about $0.04/kWh, and long-distance high-voltage dc transmission, which in their work costs $0.007/kWh.

[g] Average price (in 2007 dollars) of conventional (mainly fossil-fuel) electricity generation and transmission in all end-use sectors in the U. S. in 2007, and projected for the year 2030 (EIA, 2009a, Table A8). Excludes cost of electricity distribution ($0.024/kWh [EIA, 2009a, Table A8]), which is not included in the cost estimates for WWS and is the same for all centralized power systems.

For the unsubsidized costs of land-based wind energy to be similar to the costs of a new coal-fired power plant, the annual-average wind speed at 80 meters must be at least 6.9 m/s (15.4 mph). Data analyses indicate that 15% of the data stations (and thus, statistically, land area) in the United States (and 17% of land plus coastal offshore data stations) have wind speeds above this threshold. Globally, 13 % of stations are above the threshold.

For tidal power, water current speeds need to be at least 4 knots (2.05 m/s) for tidal energy to be economical. In comparison, wind speeds over land need to be about 7 m/s or faster for wind energy to be economical.

Solar power is relatively expensive today, but is projected to be cost-competitive by as early as 2020. Because solar PV systems can supply an enormous amount of power (Table 2), but presently are relatively expensive (Table 6), it is important to understand the potential for reducing costs. The fully annualized $/kWh cost of a PV system depends on the manufacturing cost of the PV module, the efficiency of the module, the intensity of solar radiation, the design of the system, the balance-of-system costs, and other factors. The manufacturing cost, in turn, depends on the scale of production, technological learning, profit structures, and other factors. A recent careful analysis of the potential for reducing the cost of PV systems concludes that within 10 years costs could drop to about $0.10/kWh, including the cost of compressed-air storage and long-distance high-voltage dc transmission (Table 6; Fthenakis et al., 2009). The same analysis estimated that CSP systems with sufficient thermal storage to enable them to generate electricity at full capacity 24 hours a day in spring, summer, and fall in sunny locations could deliver electricity at $0.10/kWh or less.

Thus far we have compared alternatives in terms of the cost per unit of energy delivered (i.e., $/kWh), but ideally we want to compare alternatives on the basis of the cost per unit of service provided, the difference between the two being in the cost of the end-use technologies that use energy to provide services such as heating and transportation. In the residential, commercial, and industrial sectors the end-use technologies in a WWS world for the most part will be the same as those in our current fossil-fuel world (motors, heating and cooling devices, lights, appliances, and so on), and hence in these sectors the economics of end-use will not be different in a WWS world. However, the transportation sector in a WWS world will be powered by batteries or fuel cells driving electric motors rather than by liquid fuels burned in heat engines, and so in the transportation sector we should compare the economics of electric vehicles with the economics of combustion-engine vehicles. Detailed albeit somewhat dated analyses have indicated that mass-produced BEVs with advanced lithium-ion or nickel metal-hydride batteries could have a full lifetime cost per mile (including annualized initial costs and battery replacement costs) comparable to that of a gasoline vehicle when gasoline sells for between $2.5 and $5 per gallon in the U.S. (the "break-even" gasoline price) (Delucchi and Lipman, 2001). More recent unpublished analyses using an updated and expanded version of the same model indicate breakeven prices at the lower end of this range, around $3 per gallon. This is the price of gasoline in the U. S. in summer 2009, and less than the $4 per gallon price projected by the EIA for the year 2030 EIA, 2009a, Table A12). We therefore conclude that mass-produced advanced electric vehicles using WWS power can deliver transportation services economically.

Nevertheless, in the near term, some key WWS technologies will remain relatively expensive. To the extent that WWS power is significantly more costly than fossil power, some combination of subsidies for WWS power and environmental taxes on fossil power will be needed to make WWS power economically feasible today. We turn to this issue next.

Policy approaches

Current energy markets, institutions, and policies have been developed to support the production and use of fossil fuels. Because fossil-fuel energy systems have different production, transmission, and end-use costs and characteristics than do WWS energy systems, new policies will be needed to ensure that WWS systems develop as quickly and broadly as is socially desirable. Feed-in tariffs (FITs), which essentially are subsidies to cover the difference between generation cost and wholesale electricity prices, are especially effective at stimulating generation from renewable fuels (Fthenakis et al., 2009; Sovacool and Watts, 2009). Combining FITs with a so-called "declining clock auction," in which the right to sell power to the grid goes to the bidders willing to do it at the lowest price, provides continuing incentive for developers and generators to lower costs (New York State Energy Research and Development Authority, 2004). As the cost of producing power from WWS technologies (particularly photovoltaics) declines, FITs can be reduced and eventually phased out.

Other economic policies include eliminating subsidies for fossil-fuel energy systems[5] or taxing fossil fuel production and use to reflect its environmental damages (e.g., with "carbon" taxes that represent the expected costs of climate change due to CO_2 emissions). Note, though that current subsidies and expected environmental-damage taxes generally are smaller (and hence less effective) than FITs for the costliest WWS systems versus the cleanest fossil-fuel systems (Krewitt, 2002; Koplow, 2004; Koplow and Dernbach, 2001). They also may be less feasible politically than are FITs.

Two important non-economic programs that can help the development of WWS are managing demand, and planning and managing the development of the appropriate energy-system infrastructure (Sovacool and Watts, 2009). Reducing demand by improving the efficiency of end use or substituting low-energy activities or technologies for high-energy ones directly reduces the pressure on energy supply, which means less pressure to use higher cost, less environmentally suitable resources. And because a massive deployment of WWS technologies requires an upgraded and expanded transmission grid and the smart integration of the grid with BEVs and HFCVs as decentralized electricity storage and generation components, governments need to carefully fund, plan and manage the long-term, large scale restructuring of the electricity transmission and distribution system.

Another policy issue is how to encourage end users to adopt WWS systems or end-use technologies where those are different from conventional (fossil-fuel) systems (e.g., residential solar panels, electric vehicles). Municipal financing for residential energy-efficiency retrofits or solar installations can help end users overcome the financial barrier of the high upfront cost of these systems (Fuller et al., 2009). Purchase incentives and rebates and public support of infrastructure development can help stimulate the market for electric vehicles (Åhman, 2006). Recent comprehensive analyses have indicated that government support of a large-scale transition to hydrogen fuel-cell vehicles is likely to cost just a few tens of billions of dollars – a

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[5] The Environmental Law Institute (2009) estimates that U. S. government subsidies to fossil fuel energy amount to about $10 billion per year.

tiny fraction of the total cost of transportation (National Research Council, 2008; Greene et al., 2007, 2008).

Finally, we note that a successful rapid transition to a WWS world may require more than targeted economic policies: it may require a broad-based action on a number of fronts to overcome what Sovacool (2009) refers to as the "socio-technical impediments to renewable energy:"

> Extensive interviews of public utility commissioners, utility managers, system operators, manufacturers, researchers, business owners, and ordinary consumers reveal that it is these socio-technical barriers that often explain why wind, solar, biomass, geothermal, and hydroelectric power sources are not embraced. Utility operators reject renewable resources because they are trained to think only in terms of big, conventional power plants. Consumers practically ignore renewable power systems because they are not given accurate price signals about electricity consumption. Intentional market distortions (such as subsidies), and unintentional market distortions (such as split incentives) prevent consumers from becoming fully invested in their electricity choices. As a result, newer and cleaner technologies that may offer social and environmental benefits but are not consistent with the dominant paradigm of the electricity industry continue to face comparative rejection (p. 4500).

Changing this "dominant paradigm " may require concerted social and political efforts beyond the traditional sorts of economic incentives outlined here.

Summary

A large-scale wind, water, and solar energy system can reliably supply all of the world's energy needs, with significant benefit to climate, air quality, water quality, ecological systems, and energy security, at reasonable cost. To accomplish this, we need about 4 million 5 MW wind turbines, 90,000 300-MW solar PV plus CSP power plants, 1.9 billion 3 kW solar PV rooftop systems, and lesser amounts of geothermal, tidal, wave, and hydroelectric plants and devices.

The obstacles to realizing this are primarily social and political, not technological. As discussed above, a combination of feed-in tariffs and an intelligently expanded and re-organized transmission system may be necessary but not sufficient to enough ensure rapid deployment of WWS technologies. With sensible broad-based policies and social changes, it may be possible to convert 25% of the current energy system to WWS in 10-15 years and 85% in 20-30 years. Absent that clear direction, the conversion will take longer, potentially 40-50 years.

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APPENDIX A.1. NOTES TO TABLE 1.

TW power in 2030 (fossil-fuel case)
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 the EIA *International Energy Outlook 2008* (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.

Electrified fraction
This is the fraction of energy service demand in each sector that feasibly can be satisfied by direct electric power. For example, gas water heating and space heating can easily be converted to electric resistance heating, and liquid-fuel internal-combustion-engine vehicles easily 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 will 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:

Residential sector. We assume that 5% of fuel use for space heating and 20% of fuel use for "appliances" (mainly cooking) is *not* electrified, and then use data from Table 2.5 of the EIA's *Annual Energy Review 2007* (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.

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.

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, is *not* electrified, and then use data on manufacturing consumption of energy in the U. S. (Table 2.3 of the EIA's *Annual Energy Review 2007* [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.

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 is *not* electrified. We use data on transport energy consumption from the International Energy Agency (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.

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 the electrolytic 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 assumed that hydrogen is liquefied and burned in jet engines. (See Maniaci [2006] for a discussion of the feasibility of liquid-hydrogen-powered airplanes.) 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.

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) and the *Lifecycle Emissions Model* (LEM) (Delucchi, 2003), as follows:

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)	*AVCEM, LEM (Delucchi, 2003,2005)*
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)*

Upstream factor
This accounts for changes in sectoral energy use in upstream fuel-processing activities, in a WWS world compared with the base-case fossil-fuel world. The factors shown 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 calculations are based on the following:

Value	Parameter	*Data source*
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, 2009a, 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, 2009a, 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, 2009a, 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, 2009a, Table 6).*

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. EHCMs are discussed briefly in the text. We assume that EHCMs can achieve modest reductions in energy demand, on the order of 5% to 15% in most cases.

TW power in 2030 (WWS case)
World and 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. Calculated from the other values in the table.

APPENDIX A.2. ESTIMATES OF $/KW CAPITAL COSTS AND TOTAL AMORTIZED + OPERATING $/KWH COSTS FOR VARIOUS GENERATING TECHNOLOGIES.

Part 1. Estimates using EIA (2009a, b, c, d) parameter values.

YEAR 2008	INPUT PARAMETERS							CALCULATED RESULTS		
	Capital cost ($/kW)	Cap. factor	Life (years)	Variable O&M ($/kWh)	Fixed O&M ($/kW)	Fuel ($/$10^6$-BTU)	Fuel effic.	Levelized costs ($/kWh)	Periodic costs ($/kWh)	Total cost ($/kWh)
New coal scrubbed	2058	74%	20	0.0046	27.53	1.93	37%	$0.038	$0.022	0.061
IGCC coal	2378	74%	20	0.0029	38.67	1.93	39%	$0.044	$0.020	0.064
IGCC coal/CCS	3496	74%	20	0.0044	46.12	1.93	32%	$0.065	$0.025	0.090
NG advanced CC	948	42%	20	0.0020	11.7	8.87	51%	$0.031	$0.062	0.093
NG adv. CC/CCS	1890	42%	20	0.0029	19.9	8.87	40%	$0.062	$0.079	0.141
Geothermal	1711	90%	20	0.0000	164.64	0.00	100%	$0.027	$0.000	0.027
Hydropower	2242	65%	20	0.0024	13.63	0.00	100%	$0.047	$0.002	0.050
Wind onshore	1923	38%	20	0.0000	30.3	0.00	100%	$0.070	$0.000	0.070
Wind offshore	3851	40%	20	0.0000	89.48	0.00	100%	$0.133	$0.000	0.133
Solar thermal	5021	31%	20	0.0000	56.78	0.00	100%	$0.223	$0.000	0.223
Solar PV	6038	21%	20	0.0000	11.68	0.00	100%	$0.394	$0.000	0.394

YEAR 2030	**INPUT PARAMETERS**							**CALCULATED RESULTS**		
	Capital cost ($/kW)	**Cap. factor**	**Life (years)**	**Variable O&M ($/kWh)**	**Fixed O&M ($/kW)**	**Fuel ($/$10^6$-BTU)**	**Fuel effic.**	**Levelized costs ($/kWh)**	**Periodic costs ($/kWh)**	**Total cost ($/kWh)**
New coal scrubbed	1654	78%	20	0.0046	27.53	2.04	39%	$0.029	$0.022	0.052
IGCC coal	1804	78%	20	0.0029	38.67	2.04	46%	$0.032	$0.018	0.050
IGCC coal/CCS	2533	78%	20	0.0044	46.12	2.04	41%	$0.045	$0.021	0.066
NG advanced CC	717	46%	20	0.0020	11.7	8.34	54%	$0.021	$0.055	0.076
NG adv. CC/CCS	1340	46%	20	0.0029	19.9	8.34	46%	$0.040	$0.065	0.105
Geothermal	3942	90%	20	0.0000	164.64	0.00	100%	$0.061	$0.000	0.061
Hydropower	1920	55%	20	0.0024	13.63	0.00	100%	$0.048	$0.002	0.050
Wind onshore	1615	46%	20	0.0000	30.3	0.00	100%	$0.048	$0.000	0.048
Wind offshore	2859	40%	20	0.0000	89.48	0.00	100%	$0.099	$0.000	0.099
Solar thermal	3082	31%	20	0.0000	56.78	0.00	100%	$0.137	$0.000	0.137
Solar PV	3823	21%	20	0.0000	11.68	0.00	100%	$0.249	$0.000	0.249

Cap. factor = capacity factor; Fuel effic. = fuel efficiency; IGCC = integrated gasification combined cycle; CCS = carbon capture and sequestration; CC = combined cycle; PV = photovoltaic.

Capital costs in 2008 and 2030 are from Table 8.13 of the EIA's *Assumptions to the Annual Energy Outlook 2009* (EIA, 2009b). The capital costs are "total overnight costs," and include project contingency, technological optimism factors, and learning factors. Costs pertain to projects online in the given year. In year-2007 dollars.

Capacity factors for renewables are from Table 13.2 of the EIA's *Assumptions to the Annual Energy Outlook 2009* (EIA, 2009b). The EIA shows values for the year 2012 (which we use for 2008) and the year 2030. Capacity factor for coal and natural gas for 2008 assumed to be equal to actual average capacity factors for coal and NG in 2007, as reported in Table A6 of the EIA's *Electric Power Annual 2007* (2009d). Capacity factors for coal and natural gas for 2030 assumed to be 5% (coal) or 10% (NG) higher than in 2007, because the EIA (2009d) data indicate that the capacity factor is increasing over time.

Lifetime based on this statement in EIA's NEMS documentation: "Technologies are compared on the basis of total capital and operating costs incurred over a 20-year period" (EIA, 2009c, p. 5).

Variable O&M and fixed O&M are from Table 8.2 of the EIA (2009b). The EIA shows only one set of values; we assume these are the same in 2030 and 2008. In year-2007 dollars.

Fuel costs for coal and natural gas used in the electricity sector are from Table 3 of EIA's *Annual Energy Outlook* (EIA, 2009a).

Combustion efficiency is calculated from heat rates shown in Table 8.2 of the EIA (2009b). That Table shows the rate in 2008 and the rate for the "nth-of-a-kind plant," which we assume applies to the year 2030. (Elsewhere in that report, the EIA states that "heat rates for fossil-fueled technologies are assumed to decline linearly through 2025" [EIA, 2009b, p. 88].) We assume that BTUs are based on higher heating values, which is the EIA's usual convention.

Discount rate estimate is based on the EIA's estimate of the weighted average cost of capital (WACC). In Figure 9 of the documentation for the electricity module of the National Energy Modeling System (NEMS), the estimated WACC is shown to be about 10.4% in 2008 and 10.2% in 2030 (EIA, 2009c). We assume a value of 10.3%.

Part 2. Estimates using alternative values for WWS capital cost in year 2030, lifetime, and discount rate

YEAR 2008	INPUT PARAMETERS							CALCULATED RESULTS		
	Capital cost ($/kW)	Cap. factor	Life (years)	Variable O&M ($/kWh)	Fixed O&M ($/kW)	Fuel ($/$10^6$-BTU)	Fuel effic.	Levelized costs ($/kWh)	Periodic costs ($/kWh)	Total cost ($/kWh)
New coal scrubbed	2058	74%	30	0.0046	27.53	1.93	37%	$0.026	$0.022	0.048
IGCC coal	2378	74%	30	0.0029	38.67	1.93	39%	$0.030	$0.020	0.050
IGCC coal/CCS	3496	74%	30	0.0044	46.12	1.93	32%	$0.044	$0.025	0.069
NG advanced CC	948	42%	30	0.0020	11.7	8.87	51%	$0.021	$0.062	0.083
NG adv. CC/CCS	1890	42%	30	0.0029	19.9	8.87	40%	$0.042	$0.079	0.121
Geothermal	1711	90%	30	0.0000	164.64	0.00	100%	$0.018	$0.000	0.018
Hydropower	2242	65%	30	0.0024	13.63	0.00	100%	$0.032	$0.002	0.034
Wind onshore	1923	38%	30	0.0000	30.3	0.00	100%	$0.047	$0.000	0.047
Wind offshore	3851	40%	30	0.0000	89.48	0.00	100%	$0.089	$0.000	0.089
Solar thermal	5021	31%	30	0.0000	56.78	0.00	100%	$0.150	$0.000	0.150
Solar PV	6038	21%	30	0.0000	11.68	0.00	100%	$0.265	$0.000	0.265

YEAR 2030	INPUT PARAMETERS							CALCULATED RESULTS		
	Capital cost ($/kW)	Cap. factor	Life (years)	Variable O&M ($/kWh)	Fixed O&M ($/kW)	Fuel ($/$10^6$-BTU)	Fuel effic.	Levelized costs ($/kWh)	Periodic costs ($/kWh)	Total cost ($/kWh)
New coal scrubbed	1654	78%	30	0.0046	27.53	2.04	39%	$0.020	$0.022	0.042
IGCC coal	1804	78%	30	0.0029	38.67	2.04	46%	$0.022	$0.018	0.040
IGCC coal/CCS	2533	78%	30	0.0044	46.12	2.04	41%	$0.030	$0.021	0.052
NG advanced CC	717	46%	30	0.0020	11.7	8.34	54%	$0.014	$0.055	0.069
NG adv. CC/CCS	1340	46%	30	0.0029	19.9	8.34	46%	$0.027	$0.065	0.092
Geothermal	3942	90%	30	0.0000	164.64	0.00	100%	$0.041	$0.000	0.041
Hydropower	1920	55%	30	0.0024	13.63	0.00	100%	$0.032	$0.002	0.035
Wind onshore	1143	46%	30	0.0000	30.3	0.00	100%	$0.023	$0.000	0.023
Wind offshore	2023	40%	30	0.0000	89.48	0.00	100%	$0.047	$0.000	0.047
Solar thermal	2181	31%	30	0.0000	56.78	0.00	100%	$0.065	$0.000	0.065
Solar PV	2705	21%	30	0.0000	11.68	0.00	100%	$0.119	$0.000	0.119

Notes: all parameter values the same as in part 1, except that the discount rate is 7.0% (similar to that in Fthenakis et al., 2009), the lifetime is 30 years (as assumed in Fthenakis et al., 2009), and the capital costs for wind and solar are about 30% lower, following the EIA's "falling costs" case (EIA, 2009b, Table 8.13).