Sustainable Energy Options

Excerpted from the writings of Mark Z. Jacobson

Rather than debating whether hydraulic fracturing for natural gas development can ever be made safe, we should instead be focusing on how to convert to a truly safe and sustainable energy system, including an unqualified commitment to energy efficiencies and conservation measures. Such a system would be comprised of wind, water, and solar (WWS) power, and would be cheaper than our current fossil fuel system over the long term.

Mark Z. Jacobson, a professor of Civil and Environmental Engineering at Stanford University, has extensively studied the ability to convert to a sustainable, renewable energy system. Excerpts and conclusions from his publications are set out in this paper.

Converting to Sustainable Energy Options Can Power and Benefit Our Nation

Jacobson has developed plans for conversion for individual states, the entire United States, and the world. In his research, Jacobson found that the greatest barriers to this conversion are not "technical or even economic" but are instead "social and political."[1]

> The plans contemplate all new energy powered with WWS by 2020, about 80-85% of existing energy replaced by 2030, and 100% replaced by 2050. Electrification plus modest efficiency measures would reduce each state's end-use power demand by a mean of 37.6% with ~85% of this due to electrification and ~15% due to end-use energy efficiency improvements. Remaining 2050 all-purpose end-use U.S. power demand would be met with ~31% onshore wind, ~19% offshore wind, ~29.6% utility-scale photovoltaics (PV), ~8.6% rooftop PV, ~7.5% concentrated solar power (CSP), ~1.3% geothermal power, ~0.37% wave power, ~0.13% tidal power, and ~2.5% hydroelectric power. Over the U.S. as a whole, converting would provide ~5 million 40-year construction jobs and ~2.4 million 40-year operation jobs for the energy facilities alone, the combination of which would outweigh the ~3.9 million jobs lost. Converting would also eliminate ~62,000 (19,000-116,000) of today's U.S. air pollution premature mortalities/year and avoid ~$510 (158-1,155) billion/year in today's U.S. health costs, equivalent to ~3.15 (0.98-7.13) percent of the 2012 U.S. gross domestic product. Converting would further eliminate ~$730 billion/year in 2050 global warming costs due to U.S. emissions. The health cost savings to the U.S. plus the climate cost savings to the world due to U.S. emission reductions would equal the cost of installing a 100% WWS U.S. system within ~11.0 (7.3-15.4) years.[2]

Conversion to a 100% WWS energy infrastructure would eliminate energy-related air pollution mortality and morbidity, and the associated health costs. For example, a world conversion to a WWS system would eliminate "2.5-3 million annual air pollution deaths."[3]

> The conversion to WWS should stabilize energy prices since fuel costs would be zero. On the other hand, because the fuel costs of fossil fuels rise over time, a WWS infrastructure in 2050 would save the average U.S. consumer $4,500/person/year compared with the 2050 energy cost of fossil fuels to perform the same work. Health and climate cost savings due to WWS would be another $3,100/person/year benefit, giving a total cost savings in 2050 of $7,600/person/year due to WWS.
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> The new footprint over land required for converting the U.S. to WWS for all purposes is equivalent to ~0.44% of the U.S. land area, mostly in deserts and barren land, before accounting for land gained from eliminating the current energy infrastructure. The spacing area between wind turbines, which can be used for multiple purposes, including farmland, ranchland, grazing land, or open space, is equivalent to 1.7% of U.S. land area. Grid reliability can be maintained in multiple ways. The greatest barriers to a conversion are neither technical nor economic. They are social and political. Thus, effective polices are needed to ensure a

1 Delucchi and Jacobson, 2011. Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies, Energy Policy 39, 1170.

2 Jacobson et al., 2014. 100% Wind, Water, Sunlight (WWS) All-Sector Energy Plans for the 50 United States, July 17, 2014 *Draft*, 1.

3 Jacobson, 2012. Why Natural Gas Warms the Earth More but Causes Less Health Damage Than Coal, so is not a Bridge Fuel nor a Benefit to Climate Change, October 31, 2012 *Draft*, 1.

rapid transition."[4]

Jacobson's roadmaps for states to convert to WWS detail anticipated infrastructure changes.

> In brief, [conversion] requires or results in the following changes:
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> (1) Replace fossil-fuel electric power generators with wind tur- bines, solar photovoltaic (PV) plants and rooftop systems, concentrated solar power (CSP) plants, solar hot water heater systems, geothermal power plants, a few additional hydro-electric power plants, and a small number of wave and tidal devices.
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> (2) Replace all fossil-fuel combustion for transportation, heating and cooling, and industrial processes with electricity, hydrogen fuel cells, and a limited amount of hydrogen combustion. Battery-electric vehicles (BEVs), hydrogen fuel cell vehicles (HFCVs), and BEV–HFCV hybrids…will replace all combustion-based passenger vehicles, trucks, buses, non-road machines, and locomotives sold...Long-distance trucks will be primarily BEV-HFCV hybrids and HFCVs. Ships…will similarly run on hydrogen fuel cells and electricity. Today, hydrogen-fuel-cell ships, tractors, forklifts, buses, passenger vehicles, and trucks already exist, and electric vehicles, ferries, and non-road machinery also exist. Electricity-powered air- and ground-source heat pumps, heat exchangers, and backup electric resistance heaters will replace natural gas and oil for home heating and air conditioning. Air- and ground-source heat pump water heaters powered by electricity and solar hot water preheaters will provide hot water for homes. High-temperatures for industrial processes will be obtained with electricity and hydrogen combustion. Petroleum products may still be used for lubrication and plastics as necessary, but such products will be produced using WWS power for process energy.
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> (3) Reduce energy demand beyond the reductions described under (2) through energy efficiency measures. Such measures include retrofitting residential, commercial, institutional, and government buildings with better insulation, improving the energy-out/energy-in efficiency of end uses with more efficient lighting and the use of heat-exchange and filtration systems; increasing public transit and telecommuting, designing future city infrastructure to facilitate greater use of clean-energy transport; and designing new buildings to use solar energy with more daylighting, solar hot water heating, seasonal energy storage, and improved passive solar heating in winter and cooling in summer.
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> (4) Boost economic activity by implementing the measures above. Increase jobs in the manufacturing and installation industries and in the development of new and more efficient technologies. Reduce social costs by reducing health-related mortality and morbidity and reducing environmental damage to lakes, streams, rivers, forests, buildings, and statues resulting from air and water pollution. Reduce social costs by slowing the increase in global warming and its impacts on coastlines, agriculture, fishing, heat stress, severe weather, and air pollution (which otherwise increases with increasing temperatures). Reduce long-term macroeconomic costs by eliminating exposure to future rises in fossil fuel prices.
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> (5) The plan anticipates that the fraction of new electric power generators as WWS will increase starting today such that, by 2020, all new generators will be WWS generators. Existing conventional generators will be phased out over time, but by no later than 2050. Similarly, BEVs and HFCVs should be nearly the only new vehicles…sold…by 2020. The growth of electric vehicles will be accompanied by a growth of electric charging stations in residences, commercial parking spaces, service stations, and highway rest stops.
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> (6) All new heating and cooling technologies installed by 2020 should be WWS technologies and existing technologies should be replaced over time, but by no later than 2050.
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> (7) To ensure reliability of the electric power grids, several methods should be used to match renewable energy supply with demand and to smooth out the variability of WWS resources. These include (A) combining geographically-dispersed WWS resources as a bundled set of resources rather than as separate resources and using hydroelectric power to fill remaining gaps; (B) using demand-response grid management to shift times of demand to match better with the timing of WWS power supply; (C)

4 Jacobson et al., 2014. 100% Wind, Water, Sunlight (WWS) All-Sector Energy Plans for the 50 United States, July 17, 2014 *Draft*, 1-2.

over- sizing WWS peak generation capacity to minimize the times when available WWS power is less than demand and to provide power to produce heat for air and water and hydrogen for transportation and heating when WWS power exceeds demand; (D) integrating weather forecasts into system operation to reduce reserve requirements; (E) storing energy in thermal storage media, batteries or other storage media at the site of generation or use; and (F) storing energy in electric-vehicle batteries for later extraction (vehicle-to-grid)."[5]

Why Wind, Water and Solar Are the Best Technology Options to Fuel Our Healthy Future

Jacobson's state roadmaps rely on technologies that will reduce air and water pollution and global warming impacts.

> The WWS energy technologies chosen…exist and were ranked the highest among several proposed energy options for addressing pollution and public health, global warming, and energy security (Jacobson, 2009). That analysis used a combination of 11 criteria (carbon dioxide equivalent emissions, air-pollution mortality and morbidity, resource abundance, footprint on the ground, spacing required, water consumption, effects on wildlife, thermal pollution, water, chemical pollution/radioactive waste, energy supply disruption, and normal operating reliability) to evaluate each technology. Mined natural gas and liquid biofuels are excluded from the…plan for the reasons given below.[6]

Natural gas was excluded from Jacobson's analysis

> for several reasons. The mining, transport, and use of conventional natural gas for electric power results in at least 60–80 times more carbon-equivalent emissions and air pollution mortality per unit electric power generated than does wind energy over a 100-year time frame. Over the 10–30 year time frame, natural gas is a greater warming agent relative to all WWS technologies and a danger to the Arctic sea ice due to its leaked methane and black carbon-flaring emissions…Natural gas mining, transport, and use also produce carbon monoxide, ammonia, nitrogen oxides, and organic gases. Although natural gas emits less carbon dioxide per unit electric power than coal, two factors cause natural gas to increase global warming relative to coal: higher methane emissions and less sulfur dioxide emissions per unit energy than coal…[N]atural gas is not a near-term 'low' greenhouse-gas alternative, in absolute terms or relative to coal. Moreover, it does not provide a unique or special path to renewable energy, and as a result, it is not bridge fuel and is not a useful component of a sustainable energy plan.
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> Rather than use natural gas in the short term, [Jacobson et al.,] propose[s] to move to a WWS-power system immediately, on a worldwide scale, because the Arctic sea ice may disappear in 20–30 years unless global warming is abated (e.g., Pappas, 2012). Reducing sea ice uncovers the low-albedo Arctic Ocean surface, accelerating global warming in a positive feedback. Above a certain temperature, a tipping point is expected to occur, accelerating the loss to complete elimination (Winton, 2006). Once the ice is gone, regenerating it may be difficult because the Arctic Ocean will reach a new stable equilibrium (Winton, 2006). The only potential method of saving the Arctic sea ice is to eliminate emissions of short-lived global warming agents, including methane (from natural gas leakage and anaerobic respiration) and particulate black carbon (from natural gas flaring and diesel, jet fuel, kerosene burning, and biofuel burning)."[7]

Jacobson's References

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Winton, M., 2006. Does the Arctic sea ice have a tipping point? Geophysical Research Letters 33, L23504, http://dx.doi.org/10.1029/2006GL028017.

Converting to Sustainable Energy Is Feasible

Jacobson has documented that we have the sustainable energy capacity necessary to power the United States.

5 Jacobson et al., 2013. Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight, Energy Policy 57, 586.

6 For reasons why nuclear power and coal with carbon capture are also excluded, see Jacobson and Delucchi (2011).

7 Jacobson et al., 2013. Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight, Energy Policy 57, 586-587.

The United States has more wind, solar, geothermal, and hydroelectric resources than is needed to supply the country's energy for all purposes in 2050. In this section, U.S. wind, solar, geothermal, hydroelectric, tidal, and wave resources are examined.

Wind

…Results suggest that the U.S. mean onshore capacity factor may be 30.5% and offshore, 37.3%. Locations of strong onshore wind resources include the Great Plains, northern parts of the northeast, and many areas in the west. Weak wind regimes include the southeast and the westernmost part of the west coast continent. Strong offshore wind resources occur off the east coast north of South Carolina and the Great Lakes. Very good offshore wind resources also occur offshore the west coast and offshore the southeast and gulf coasts…[T]he 2050 clean-energy plans require 1.7% of U.S. onshore land and 0.88% of U.S. onshore-equivalent land area sited offshore for wind-turbine spacing to power 50% of all-purpose 2050 U.S. energy. The mean capacity factor for onshore wind needed is 35.2% and that for offshore wind is 42.5%. Figure 1 suggests that much more land and ocean areas with these respective capacity factors or higher are available than are needed for the plans.

Solar

…The best solar resources in the U.S. are broadly in the Southwest, followed by the Southeast, the Northwest, then the Northeast. The land area in 2050 required for non-rooftop solar under the plan here is equivalent to ~0.41% of U.S. land area, which is a very small percent of area relative to the area of strong solar resources available in Figure 2 and in other solar resource analyses. As such, we do not believe there is a limitation in solar resources available for implementing the 50 state plans proposed …

Geothermal

The U.S. has significant traditional geothermal resources (volcanos, geysers, and hot springs) as well as heat stored in the ground due to heat conduction from the interior of the Earth and solar radiation absorbed by the ground. In terms of traditional geothermal, the U.S. has an identified resource of 9.057 GW[8] deliverable power distributed over 13 states, undiscovered resources of 30.033 GW deliverable power, and enhanced recovery resources of 517.8 GW deliverable power (USGS, 2008). As of April, 2013, 3.386 GW of geothermal capacity had been installed in the U.S. and another 5.15-5.523 GW was under development (GES, 2013).

States with identified geothermal resources (and the percent of resource available in each state) include Colorado (0.33%), Hawaii (2.0%), Idaho (3.68%), Montana (0.65%), Nevada (15.36%), New Mexico (1.88%), Oregon (5.96%), Utah (2.03%), Washington State (0.25%), Wyoming (0.43%), Alaska (7.47%), Arizona (0.29%), and California (59.67%). All states have the ability to extract heat from the ground for heat pumps. However, such energy would not be used to generate electricity; instead it would be used directly for heat, thereby reducing electric power demand for heat although electricity would still be needed to run heat pumps…

Hydroelectric

Under the plan proposed here, conventional hydro will supply 47.26 GW of delivered power, or 2.46% (Table 1) of U.S. 2050 total end-use power demand for all purposes. Thus, 2010 U.S. plus Canadian delivered hydropower (34.8 GW) already provides 73.6% of the U.S. 2050 delivered hydropower power goal. The plan here calls for very few new hydroelectric dams. Thus, the additional 12.5 GW of delivered hydro would be obtained by increasing the capacity factor of existing dams to an average of 53.1%. Existing dams currently provide less than their maximum capacity due to an oversupply of energy available from other sources and multiple priorities affecting water use…

Tidal

Tidal (or ocean current) is proposed to comprise about 0.13% of U.S. total power in 2050 (Table 1). The U.S. currently has the potential to generate 50.8 GW (445 TWh/yr)[9] of delivered power from tidal streams (Georgia Tech Research Corporation, 2011). States with the great-

8 GW or gigawatt. One GW is equal to one billion watts or 1,000 megawatts (MW).

9 TWh, or terawatt hour. One TW is equal to one trillion watts.

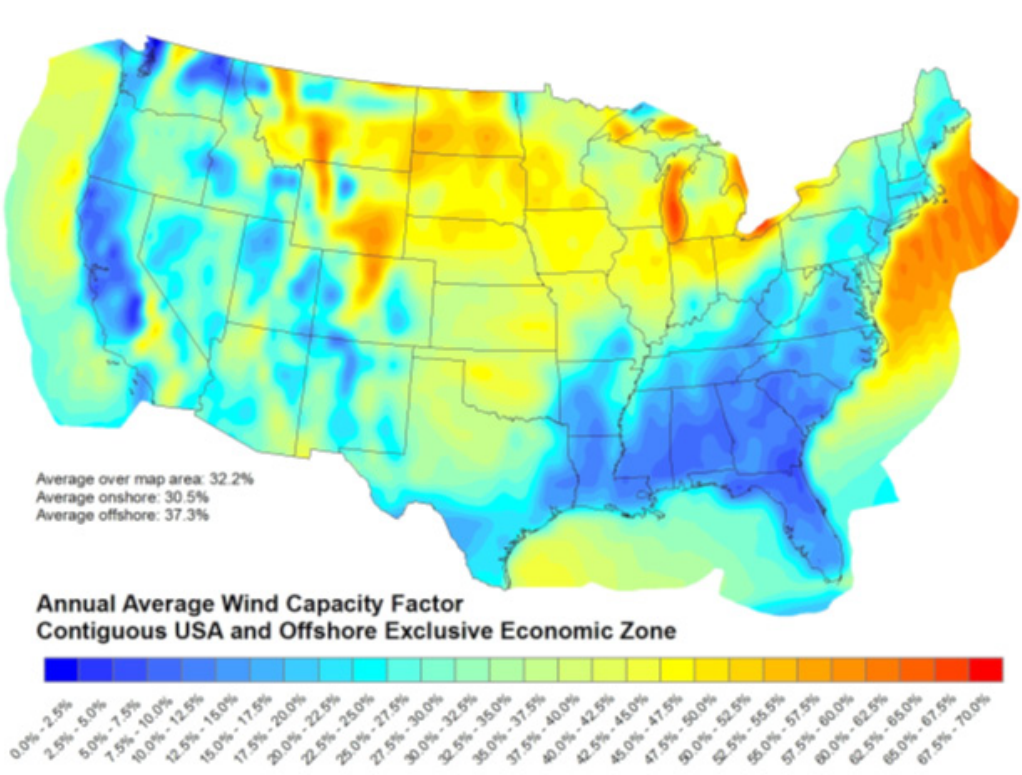

Figure 1. Modeled 2006 annually averaged capacity factor for 5 MW RePower wind turbines (126-m diameter rotor) at 100-m hub height above the topographical surface in the contiguous United States. The model used was GATOR-GCMOM (Jacobson et al., 2007; Jacobson, 2010), which was nested for one year from the global to regional scale with resolution on the regional scale of 0.6 degrees W-E x 0.5 degrees S-N.

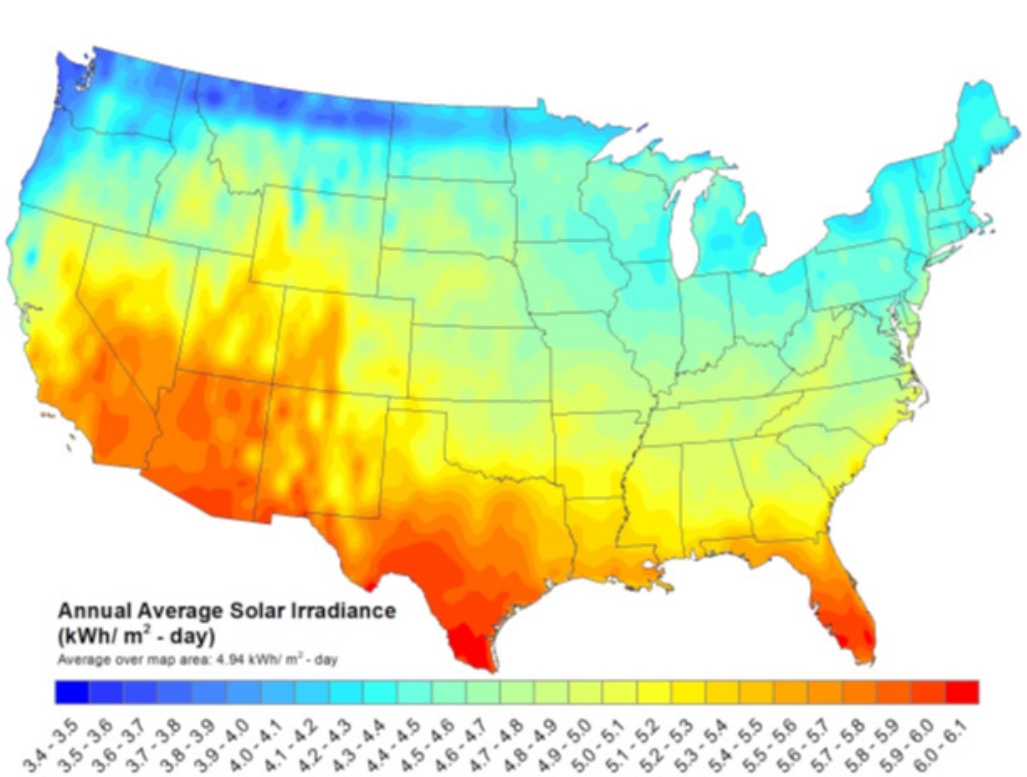

Figure 2. Modeled 2013 annual downward direct plus diffuse solar radiation at the surface (kWh/m2/day) available to photovoltaics in the contiguous United States. The model used was GATOR-GCMOM (Jacobson et al., 2007; Jacobson, 2010), which simulates clouds, aerosols gases, weather, radiation fields, and variations in surface albedo over time. The model was nested from the global to regional scale with resolution on the regional scale relatively coarse (0.6 deg W-E x 0.5 deg S-N).

Energy Technology	Rated power of one plant or device (MW)	Percent of 2050 power Demand met by plant/device	Nameplate capacity of existing plus new plants or devices (MW)	Percent of nameplate capacity already installed 2013	Number of new plants or devices needed for U.S.	Percent of U.S. land area for footprint of new plants / devices[A]	Percent of U.S. land area for spacing of new plants / devices
Onshore wind	5	30.98	1,818,769	3.36	351,547	0.00005	1.7057
Offshore wind	5	18.99	904,726	0.00	180,945	0.00002	0.8779
Wave device	0.75	0.37	33,657	0.00	44,876	0.00026	0.0122
Geothermal plant	100	1.29	28,935	8.32	265	0.00099	0.0000
Hydroelectric plant	1300	2.46	92,816	95.92	4	0.02701	0.0000
Tidal turbine	1	0.13	10,687	0.00	10,687	0.00003	0.0004
Res. roof PV	0.005	4.73	641,416	0.55	127,573,149	0.05208	0.0000
Com/gov roof PV	0.1	3.89	495,593	0.36	4,938,184	0.04032	0.0000
Solar PV plant[B]	50	29.62	2,923,981	0.06	58,444	0.23859	0.0000
Utility CSP plant	100	7.54	833,012	0.00	8,330	0.17275	0.0000
Total		100.00	7,783,592	2.05	0	0.53	2.60
Total new land[C]						0.44	1.71

A Total land area for each state is given in Jacobson, M.Z., G. Bazouin, and M.A. Delucchi, 2014a. Spreadsheets of calculations for this study. http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html.

B The solar PV panels used for this calculation are Sun Power E20 panels. The capacity factors used for residential and commercial/government rooftop solar production estimates are given in Jacobson et al. (2014a) for each state. For utility solar PV plants, nominal "spacing" between panels is included in the plant footprint area. The capacity factors assumed for utility PV are given in Jacobson et al. (2014a).

C The footprint area requiring new land is equal to the footprint area for new onshore wind, geothermal, hydroelectric, and utility solar PV. Offshore wind, wave and tidal are in water, and so do not require new land. The footprint area for rooftop solar PV does not entail new land because the rooftops already exist and are not used for other purposes (that might be displaced by rooftop PV). Only onshore wind entails new land for spacing area. The other energy sources either are in water or on rooftops, or do not use additional land for spacing. Note that the spacing area for onshore wind can be used for multiple purposes, such as open space, agriculture, grazing, etc.

Table 1. Number, capacity, footprint area, and spacing area of WWS power plants or devices needed to provide the U.S. total annually-averaged end-use power demand for all purposes in 2050, accounting for transmission, distribution, and array losses. Individual tables for each state and their derivation are given in Jacobson et al. (2014a).

…Short- and moderate distance transmission and distribution losses for offshore wind and all other energy sources treated here were assumed to be 5-10%. Since each state's plan is self-contained, extra-long distance transmission was assumed not necessary. However, If it were needed, losses from it would be 1.4-6% per 1000 km plus 1.3-1.8% in the station equipment (Delucchi and Jacobson, 2011).

est potential offshore tidal power include Alaska (47.4 GW), Washington State (683 MW), Maine (675 MW), South Carolina (388 MW), New York (280 MW), Georgia (219 MW), California (204 MW), New Jersey (192 MW), Florida (166 MW), Delaware (165 MW), Virginia (133 MW), Massachusetts (66 MW), North Carolina (66 MW), Oregon (48 MW), Maryland (35 MW), Rhode Island (16 MW), Alabama (7 MW), Texas (6 MW), Louisiana (2 MW). The available power in Maine, for example, is distributed over 15 tidal streams. The present state plans call for extracting just 2.5 GW of delivered power, which would require an installed capacity of 10.7 GW of tidal turbines.

Wave

Wave power is also proposed to comprise 0.37%, or about 7.1 GW, of the U.S. total end-use power demand in 2050 (Table 1). The U.S. has a recoverable delivered power potential (after accounting for array losses) of 135.8 GW (1,190 TWh) along its continental shelf edge (EPRA, 2011). This includes 28.5 GW of recoverable power along the West Coast, 18.3 GW along the East Coast, 6.8 GW along the Gulf of Mexico, 70.8 GW along Alaska's coast, 9.1 GW along Hawaii's coast, and 2.3 GW along Puerto Rico's coast. Thus, all states border the oceans have wave power potential. The available supply is almost 20 times the delivered power needed under this plan."

…Short- and moderate distance transmission and distribution losses for offshore wind and all other energy sources treated here were as-

sumed to be 5-10%. Since each state's plan is self-contained, extra-long distance transmission was assumed not necessary. However, If it were needed, losses from it would be 1.4-6% per 1000 km plus 1.3-1.8% in the station equipment (Delucchi and Jacobson, 2011).[10]

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Sustainable Energy is Reliable

Jacobson has determined that WWS can provide the power when and where it is needed.

> An important concern to address in a clean -energy economy is whether electric power demand can be met with WWS supply on a minutely, daily, and seasonal basis…Several studies have examined whether up to 100% penetrations of WWS resources could be used reliably to match power with demand (e.g., Jacobson and Delucchi, 2009; Mason et al., 2010; Hart and Jacobson, 2011, 2012; Connolly et al., 2011; Elliston et al., 2012; NREL (NationalRenewableEnergyLaboratory), 2012; Rasmussen et al., 2012; Budischak et al.,2013). Using hourly load and resource data and accounting for the intermittency of wind and solar, both Hart and Jacobson (2011) and Budischak et al. (2013) found that up to 99.8% of delivered electricity could be produced carbon-free with WWS resources over multiple years…Eliminating remaining carbon emission is challenging but can be accomplished in several ways. These include using demand response and demand management, which will be facilitated by the growth of electric vehicles; oversizing the grid and using the excess power generated to produce district heat through heat pumps and thermal stores and hydrogen for other sectors of the energy economy (e.g. heat for buildings, high-temperature processes, and fuel-cell vehicles); using concentrated solar power storage to provide solar power at night; and storing excess energy at the site of generation with pumped hydroelectric power, compressed air (e.g. in underground caverns or turbine nacelles), flywheels, battery storage packs, or batteries in electric vehicles (Kempton and Tomic, 2005). Oversizing the peak capacity of wind and solar installation to exceed peak inflexible power demand can reduce the time that available WWS power supply is below demand, thereby reducing the need for other measures to meet demand. The additional energy available when WWS generation exceeds demand can be used to produce hydrogen (a storage fuel) by electrolysis for heating processes and transportation and to provide district heating. Hydrogen must be produced in any case as part of the WWS solution. Oversizing and using excess energy for hydrogen and district heating would also eliminate the current practice of shutting down (curtailing) wind and solar resources when they produce more energy than the grid can accommodate. Denmark currently uses excess wind energy for district heating using heat pumps and thermal stores (e.g., Elsman, 2009).[11]

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10 Jacobson et al., 2014. 100% Wind, Water, Sunlight (WWS) All-Sector Energy Plans for the 50 United States, July 17, 2014 *Draft*, 10-17.

11 Jacobson et al., 2013. Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight, Energy Policy 57, 591.

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Sustainable Energy Is Cost Effecient

The cost of sustainable energy will continue to decrease over time. By comparison, conventional fuel costs are expected to rise over time, making sustainable energy the better near term and long term choice based on cost.

> With a 100% WWS market penetration proposed for 2050, significant cost reductions are expected not only due to anticipated technology improvements and the zero fuel cost of WWS resources, but also due to less expensive manufacturing and streamlined project deployment from increased economies of scale. On the other hand, private electricity costs of conventional fuels are expected to continue to rise.
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> Costs of onshore wind and hydroelectric power are expected to remain low through 2030. The cost of wind-generated electricity has declined recently due to the rapid decline in turbine prices and improvements in technology leading to increased net capacity factors (e.g. increases in average hub height and rotor diameter). National costs of solar PV are expected to fall to 4.5-10 cents/kWh by 2030, with the low-end reduction for utility-scale solar and the high end for residential. With this expected price reduction, solar PV is expected to be competitive with other energy sources throughout the U.S. by significantly before 2030.
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> Due to the nascent state of the wave and tidal industries (the first commercial power projects have just now been deployed in the United States), it is difficult to make accurate cost estimates. Roughly 50 different tidal devices are in the proof-of-concept or prototype development stage, but large-scale deployment costs have yet to be demonstrated. Although current wave power-generating technologies appear to be expensive, they might follow a learning curve similar to that of the wind power industry. Industry analyses point toward a target annualized cost of 4-11 U.S. ¢/kWh for wave and 5-7 ¢/kWh for tidal power (Asmus and Gauntlett, 2012), although a greater understanding of costs will become available once systems in the field have been in operation for a few years.
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> …[M]any future wind and solar farms may be far from population centers, requiring long-distance transmission. For long-distance transmission, high-voltage direct-current (HVDC) lines are used because they result in lower transmission line losses per unit distance than alternating-current (AC) lines (Table 1, footnote). The cost of extra-long-distance HVDC transmission on land (1,200-2,000 km) ranges from 0.3-3 U.S. cents/kWh, with a median estimate of ~1 U.S. cent/kWh (Delucchi and Jacobson, 2011). A system with up to 25% undersea HVDC transmission would increase the additional long-distance transmission cost by less than 20%. Transmission needs and costs can be reduced by considering that decreasing transmission capacity among interconnected wind farms by 20% reduces aggregate power by only 1.6% (Archer and Jacobson, 2007).
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> … [E]ven with extra-long-distance HVDC transmission, the costs of hydroelectric and wind power are already cost competitive with fossil electricity sources. In fact, a state by-state examination of fractional electricity generation by wind versus cost of electricity by state provides the following results. From January-July 2013, two states (South Dakota and Iowa) generated nearly 28% of their electric power from wind. Nine states generated more than 13% from wind (South Dakota, Iowa, Kansas, Minnesota, North Dakota, Oklahoma, Idaho, Colorado, and Oregon). The tenth state, Texas, generated 9.3% of its electricity from wind (EIA, 2013a). The average increase in residential electricity price from 2003-2013 in the 10 states with the highest fraction of their electricity from wind was 3 ¢/kWh. The price increase during the same period in all other 40 states was 4 ¢/kWh. The price increase in Hawaii during the same period

was 19.9 ¢/kWh. This result suggests that states that invested more in wind saw less of a price increase than states that invested less in wind, contrary to the perception that the addition of an intermittent renewable energy source causes an average increase in electricity price.[12]

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Sustainable Energy Options Avoid Expensive Air Pollution Costs and the Damage it Does to Our Health and Lives

Jacobson has also considered the considerable human health implications of converting to WWS.

> *The top-down approach to estimate air-pollution mortality in the U.S.* The premature human mortality rate in the U.S. due to cardiovascular disease, respiratory disease, and complications from asthma due to air pollution has been estimated conservatively by several sources to be at least 50,000-100,000 per year. In Braga et al. (2000), the U.S. air pollution mortality rate was estimated at about 3% of all deaths. The all-cause death rate in the U.S. is about 833 deaths per 100,000 people and the U.S. population in 2012 was 313.9 million. This suggests a present-day air pollution mortality rate in the U.S. of ~78,000/year. Similarly, from Jacobson (2010), the U.S. death rate due to ozone and particulate matter was calculated with a three-dimensional air pollution-weather model to be 50,000-100,000 per year. These results are consistent with those of McCubbin and Delucchi (1999), who estimated 80,000 to 137,000 due to all anthropogenic air pollution in the U.S. in 1990, when air pollution levels were higher than today.
>
> *The bottom-up approach to estimate air-pollution mortality in the U.S.* This approach involves combining measured countywide or regional concentrations of particulate matter ($PM_{2.5}$) and ozone (O_3) with a relative risk as a function of concentration and with population by county. From these three pieces of information, low, medium, and high estimates of mortality due to $PM_{2.5}$ and O_3 pollution are calculated with a health-effects equation (e.g., Jacobson, 2010)…The medium values for the U.S. for $PM_{2.5}$ were ~48,000 premature mortalities/yr…and for O_3 were ~14,000 premature mortalities/yr, with a range of 7,000-21,000/yr. Thus, overall, the bottom-up approach gives ~62,000 (19,000-116,000) premature mortalities/year for $PM_{2.5}$ plus O_3. The top-down estimate (50,000–100,000), from Jacobson (2010), falls within the bottom-up range.
>
> …[T]he total social cost [of fossil fuel-based energy] due to air pollution mortality, morbidity, lost productivity, and visibility degradation in the U.S. today is conservatively estimated from the ~62,000 (19,000-116,000) premature mortalities/yr to be $510 (158-1,155) billion/yr (using an average of $8.2 million/mortality for the low and medium numbers of mortalities and $10 million/mortality for the high number). Eliminating these costs today represents a savings equivalent to ~3.15 (0.98-7.13)% of the 2012 U.S. gross domestic product.
>
> Energy-related greenhouse gas emissions from the U.S. cause climate-related damage to the world… Ackerman et al. (2008) estimated global warming damage costs (in 2006 U.S. dollars) to the U.S. alone due to world emissions of greenhouse gases and warming aerosol particles of $271 billion/yr in 2025, $506 billion/yr in 2050, $961 billion/yr in 2075, and $1.9 trillion/yr in 2100. That analysis accounted for severe storm and hurricane damage, real estate loss, energy-sector costs, and water costs. The largest of these costs was water costs. It did not account for increases in mortality and illness due to increased heat stress, influenza, malaria, and air pollution or increases in forest-fire incidence, and as a result it probably underestimated the true cost.
>
> …[C]onverting the U.S. to WWS would avoid $510 (158-1,155) billion/year in air pollution

12 Jacobson et al., 2014. 100% Wind, Water, Sunlight (WWS) All-Sector Energy Plans for the 50 United States, July 17, 2014 *Draft*, 24-27.

health costs to the U.S. and ~$730 billion/yr in global-warming damage costs worldwide by 2050. The U.S.-mean installed capital cost of the electric power system proposed here, weighted by the proposed installed capacity of each generator, is approximately $1.8 million/MW. Thus, for new nameplate capacity, summed over all generators, of 7.63 TW (Table 1), the total capital cost of a U.S. WWS system is ~ $13.7 trillion. As such, the health-cost savings alone to the U.S. due to converting to WWS may equal the installation cost of WWS generators within 27 (12-87) years. The health-cost savings to the U.S. plus the climate-cost savings to the world may equal the generator cost within 11 (7.3-15.4) years.

…[M]odels predict the creation of ~4.95 million 40-year construction jobs and ~2.4 million 40-year operation and maintenance jobs for the WWS generators proposed. The shift to WWS will simultaneously result in the loss of ~3.88 million in the current fossil-based electricity generation, petroleum refining, and uranium production industries in the U.S. Thus, a net of ~3.48 million 40-year jobs will be created in the U.S. The direct and indirect earnings from WWS amount to $271 billion/year during the construction stage and $152 billion/yr for operation. The annual earnings lost from fossil-fuel industries total ~$233 billion/yr giving a net gain in annual earnings of ~$190 billion/yr. These numbers are not meant to be a precise forecast, but rather an indication of the economic effect WWS electricity generation may have on the U.S. The actual job and revenue impacts are subject to various uncertainties associated with progress in technology, projects scale and policies. Overall, the positive socio-economic impacts of WWS resource electricity implementation are expected to exceed significantly the negative impacts."[13]

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A Sustainable Energy Future is Achievable

Sustainable energy to fuel our future is within our grasp. To get the health, environment and economic benefits of sustainable energy and leave behind the damage of shale gas and continued use of fossil fuels, we just need to take the steps to make it happen.

> Manpower, materials, and energy resources do not constrain the development of WWS power; the obstacles to realizing this transformation are primarily social and political, not technological.[14] With clear direction in the form of broad-based policies and relatively small social changes "it may be possible for a 25% conversion in 10-15 years, 85% in 20-30 years, and 100% by 2050."[15]
>
> Least-cost energy system optimization studies and practical implementation considerations will determine the most efficient design and operation of the energy system… Several methods exist to match renewable energy supply with demand and to smooth out the variability of WWS resources" and to reduce costs associated with the transition.[16]

In the United States, approximately 40% of the total annual carbon dioxide emissions are associated with the generation of electricity.[17] Implementation of a WWS energy system will essentially "eliminate the costs related to these emissions such as energy-related global warming; air, soil, and water pollution; and energy insecurity.[18]

13 Jacobson et al., 2014. 100% Wind, Water, Sunlight (WWS) All-Sector Energy Plans for the 50 United States, July 17, 2014 *Draft*, 36.

14 Delucchi and Jacobson, 2011. Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies, Energy Policy 39, 1170.

15 Delucchi and Jacobson, 2011. Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies, Energy Policy 39, 1179.

16 Jacobson, et al., 2014. A 100% Wind, Water, Solar (WWS) All-Sector Energy Plan for Washington State, July 14, 2014 *Draft*, 44.

17 Hart and Jacobson, 2011, A Monte Carlo approach to generator portfolio planning and carbon emissions assessments of systems with large penetrations of variable renewables, Energy Policy 36, 2278, citing Energy Information Administration. Annual energy outlook 2009, table a18, http://www.eia.doe.gov/oiaf/aeo/pdf/appendixes.pdf; 2009.

18 Jacobson, et al., 2014. A 100% Wind, Water, Solar (WWS) All-Sector Energy Plan for Washington State, July 14, 2014 *Draft*, 46.