100% Wind, Water, Sunlight (WWS) All-Sector Energy Plans for the 50 United States

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By

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Abstract

This study presents roadmaps for each of the 50 United States to reduce demand and convert their all-purpose energy infrastructures (for electricity, transportation, heating/cooling, and industry) to ones derived entirely from wind, water, and sunlight (WWS) generating electricity and electrolytic hydrogen while maintaining jobs and low energy prices. The numbers of devices, footprint and spacing areas, energy costs, numbers of jobs, air pollution and climate benefits, and policies needed for the conversions are provided for each state. 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. 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. 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 rapid transition.

Keywords: Renewable energy; air pollution; global warming; sustainability

1. Introduction

This paper presents roadmaps to convert each of the 50 U.S. states' all-purpose (electricity, transportation, heating/cooling, and industry) energy infrastructures to ones powered by wind, water, and sunlight (WWS). Existing energy plans in many states address the need to reduce greenhouse gas emissions and air pollution, keep energy prices low, and foster jobs. Goals in many states are limited to partial emission reductions by 2050. The roadmaps proposed here outline not only how existing goals can be reached but also how more aggressive goals, namely eliminating 80-85% of present-day greenhouse gas and air pollutant emissions by 2030 and 100% by 2050 can be reached while growing the number of jobs and stabilizing energy prices.

Each roadmap is similar in outline to those recently developed for New York, California, and Washington State (Jacobson et al., 2013; 2014a,b). However, future energy demand, the numbers of WWS generators needed to meet such demand, and proposed policy measures are developed here uniquely for each state. The roadmaps also include originally-derived (1) state-by-state air-pollution mortality numbers and costs based on pollution data from all monitoring stations in each state, (2) a determination of state-by-state rooftop areas and potential solar PV installation over residential and commercial/government buildings and associated carports, garages, parking lots, and parking structures, (3) potential job creation and loss by state, (4) estimates of the future cost of energy and of avoided global-warming costs by state, and (5) footprint and spacing areas needed for WWS generators in each state. This paper further provides a transition timeline, energy efficiency measures, and proposed first steps.

2. How the Technologies Were Chosen

The WWS energy technologies chosen are existing technologies ranked the highest among several proposed energy options for addressing pollution, public health, global warming, and energy security (Jacobson, 2009). That ranking study concluded that, for electricity; wind, concentrated solar power (CSP), geothermal, solar photvoltaics (PV), tidal, wave, and hydroelectric power, all WWS technologies, were the best overall options. For transportation, battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (HFCVs), where the hydrogen is produced by electrolysis from WWS electricity were ranked the highest. BEVs with fast charging or battery swapping would power long-distance, light-duty transportation. Heavy-duty transportation would be carried out by BEV-HFCV hybrids. Heating/cooling would be powered primarily by electric heat pumps (ground-, air-, or water-source) with some electric-resistance heating. High-temperature industrial processes would be powered by electricity and combusted electrolytic hydrogen.

Hydrogen fuel cells would be used only for transportation, not for electric power generation due to the inefficiency of that application for HFCVs. Although electrolytic hydrogen for transportation is less efficient and more costly than is electricity for BEVs, some segments of transportation may benefit from the use of hydrogen fuel cells (e.g., ships, aircraft, long-distance freight). These plans also include energy efficiency measures but not nuclear power, coal with carbon capture, liquid or solid biofuels, or natural gas for the reasons discussed in Jacobson and Delucchi (2011) and Jacobson et al. (2013).

3. Change in U.S. Power Demand upon Conversion to WWS

Table 1 summarizes the calculated state-by-state end-use power demand by sector in 2050 if conventional fuel use continues along a business-as-usual (BAU) trajectory. It also shows the new demand upon a conversion to a 100% WWS infrastructure (zero fossil fuels, biofuels, or nuclear fuels). The table was derived from a spreadsheet of annually averaged end-use power demand data as in Jacobson and Delucchi (2011). All end uses that feasibly could be electrified were assumed to use WWS power directly, and remaining end uses (some heating, high-temperature industrial processes, and some transportation) were assumed to use WWS power indirectly in the form of electrolytic hydrogen (hydrogen produced by splitting water with WWS electricity). End-use power excludes losses incurred during production and transmission of the power.

Under these roadmaps, electricity requirements increase, but the use of oil and gas for transportation and heating/cooling decreases to zero. Further, the increase in electricity use due to electrifying all sectors is much smaller than is the decrease in energy embodied in the gas, liquid, and solid fuels that the electricity is replacing because of the high efficiency of electricity for heating and electric motors. As a result, end use power demand decreases significantly in a WWS world (Table 1).

Table 1. 1st row of each state: estimated 2050 total end-use power demand (GW) and percent of total demand by sector if conventional fossil-fuel, nuclear, and biofuel use continue from today to 2050 under a business-as-usual (BAU) trajectory. 2nd row of each state: estimated 2050 total end-use power demand (GW) and percent of total demand by sector if 100% of BAU end-use all-purpose delivered power demand in 2050 is instead provided by WWS. The number in the first row of the "% Change" column for each state is the percent reduction in total 2050 BAU power demand due to assumed end-use energy efficiency measures; the number in the second row of the "% Change" column is the overall percent change in total 2050 demand due to a conversion from BAU to WWS and accounts not only for the end-use energy efficiency reduction, but also for demand reductions due to electrification, which is more efficient than combustion, as well as smaller demand reductions due to the removal of energy use for the upstream production of fuels (e.g., mining and processing).

	2050 Residential demand (% of total)	2050 Commercial demand (% of total)	2050 Industrial demand (% of total)	2050 Transportation demand (% of total)	2050 Total all-purpose end-use power demand (GW)	% Change due to (upper) end-use efficiency and (lower) all efficiencies
Alabama	13.2	8.6	42.1	36.1	53.3	-5.0
	17.2	12.3	53.2	17.3	34.9	-34.5
Alaska	6.3	7.8	50.7	35.2	27.9	-5.1
	7.7	10.5	65.3	16.5	17.8	-36.4
Arizona	18.2	15.4	14.5	51.9	55.5	-5.6

	27.2	25.0	20.2	27.6	32.2	-42.0
Arkansas	14.8	11.5	35.9	37.9	32.7	-5.4
	19.4	16.0	46.5	18.1	21.0	-35.8
California	14.6	11.6	23.5	50.3	279.7	-5.6
	20.8	18.9	33.9	26.4	157.5	-43.7
Colorado	19.2	12.5	29.8	38.5	50.0	-6.0
	24.1	17.9	39.2	18.8	31.6	-36.8
Connecticut	29.4	18.4	9.3	42.9	21.8	-6.4
	38.6	27.0	12.8	21.6	13.3	-39.2
Delaware	21.3	18.0	20.3	40.4	7.1	-5.7
	28.3	26.2	26.4	19.0	4.4	-38.0
Florida	17.5	14.1	14.3	54.1	160.0	-5.4
	27.7	23.7	20.3	28.3	91.3	-42.9
Georgia	17.5	11.1	25.2	46.2	99.5	-5.5
	24.4	17.6	35.1	23.0	59.4	-40.4
Hawaii	7.2	8.8	19.5	64.5	8.5	-4.8
	13.4	17.6	31.5	37.4	4.3	-49.7
Idaho	18.0	11.3	33.1	37.7	17.6	-5.6
	23.4	15.7	42.3	18.6	11.3	-35.5
Illinois	21.7	13.6	30.0	34.7	110.5	-6.1
	26.6	19.0	38.0	16.4	70.8	-35.9
Indiana	14.7	9.1	45.4	30.7	79.8	-5.2
	18.2	12.4	55.5	13.9	52.7	-34.0
Iowa	11.7	9.8	51.4	27.1	42.2	-5.4
	14.0	12.7	61.4	11.8	29.9	-29.2
Kansas	16.6	11.1	39.7	32.6	32.2	-5.7
	20.1	15.4	48.0	16.5	21.3	-33.9
Kentucky	14.4	9.0	38.4	38.2	49.5	-5.0
	19.1	12.9	49.7	18.3	31.5	-36.3
Louisiana	4.7	3.4	72.0	19.9	135.5	-4.6
	5.7	4.5	80.6	9.2	95.0	-29.9
Maine	16.7	12.2	35.6	35.5	13.8	-5.3
	21.4	16.7	45.6	16.3	8.9	-35.1
Maryland	22.7	20.2	11.7	45.4	42.9	-6.0
	31.1	30.8	15.5	22.7	25.6	-40.3
Massachusetts	28.4	16.6	12.0	43.0	41.8	-6.4
	37.1	24.3	17.2	21.3	25.1	-40.0
Michigan	24.8	15.4	22.9	36.9	76.8	-6.4
	30.8	21.5	29.7	17.9	48.7	-36.6
Minnesota	17.2	13.1	35.1	34.6	60.6	-5.7
	21.2	18.0	44.4	16.4	39.2	-35.3
Mississippi	12.7	8.8	35.8	42.7	33.5	-5.3
	17.3	13.1	47.2	22.4	20.9	-37.6
Missouri	21.5	14.3	19.3	44.9	51.6	-5.8
	29.7	21.9	26.2	22.2	31.0	-40.0
Montana	17.2	13.4	32.0	37.3	12.1	-5.8
	22.3	18.7	40.0	19.0	7.6	-36.6
Nebraska	14.1	11.3	44.7	29.9	23.4	-5.4
	16.8	14.9	54.6	13.7	15.9	-32.1
Nevada	19.2	14.2	20.6	46.0	27.2	-5.7
	26.4	21.4	29.0	23.2	16.2	-40.5
New Hampshire	23.9	16.1	12.0	48.0	9.9	-5.7
	33.8	25.1	16.8	24.3	5.7	-42.2

New Jersey	20.0	18.3	10.6	51.1	75.5	-6.3
	28.3	29.3	15.1	27.3	41.7	-44.8
New Mexico	14.4	11.8	35.5	38.3	20.5	-5.5
	18.6	16.8	45.7	18.9	13.0	-36.8
New York	28.1	25.4	9.3	37.2	93.4	-6.6
	35.1	35.2	11.8	17.9	59.4	-36.4
North Carolina	20.3	15.1	21.6	43.0	81.9	-5.5
	27.9	22.7	28.8	20.6	50.9	-37.9
North Dakota	8.7	8.2	56.2	26.9	13.5	-5.1
	10.8	11.2	64.0	14.0	9.3	-31.2
Ohio	20.0	13.1	31.0	35.9	99.5	-5.8
	25.2	18.3	39.7	16.8	63.5	-36.2
Oklahoma	14.0	10.1	38.9	36.9	46.3	-5.5
	17.9	14.3	49.2	18.6	29.9	-35.4
Oregon	17.8	12.8	23.3	46.1	33.0	-5.6
	25.0	19.6	32.3	23.0	19.9	-39.8
Pennsylvania	20.4	13.0	30.1	36.5	102.4	-5.8
	25.8	18.3	37.8	18.1	65.2	-36.3
Rhode Island	29.1	17.6	13.6	39.7	6.2	-6.4
	37.2	25.6	17.6	19.6	3.8	-38.5
South Carolina	15.0	10.3	30.5	44.1	45.2	-5.0
	21.1	15.9	41.7	21.2	27.7	-38.7
South Dakota	12.3	10.2	45.0	32.5	11.1	-5.4
	15.1	13.9	55.5	15.5	7.4	-33.2
Tennessee	17.6	11.8	28.3	42.2	63.8	-5.4
	24.2	17.7	37.6	20.5	39.3	-38.4
Texas	8.0	6.9	54.8	30.3	469.0	-4.8
	10.4	9.9	65.5	14.2	304.6	-35.0
Utah	18.3	14.3	26.0	41.5	28.3	-6.0
	23.4	20.8	34.5	21.3	17.3	-38.9
Vermont	26.9	14.9	13.0	45.2	4.7	-5.8
	37.4	22.5	18.0	22.1	2.8	-40.5
Virginia	19.0	16.1	18.9	46.0	74.1	-5.5
	26.6	24.9	25.6	22.9	44.4	-40.0
Washington	16.2	12.3	26.9	44.6	67.7	-5.4
	22.5	18.8	36.6	22.0	40.8	-39.8
West Virginia	16.7	11.2	38.2	33.9	18.1	-5.7
	21.2	15.1	45.8	17.9	12.0	-33.4
Wisconsin	20.2	13.8	31.2	34.7	51.1	-5.8
	25.3	19.0	39.8	15.8	33.1	-35.2
Wyoming	6.9	7.8	55.2	30.1	15.3	-5.0
	8.2	10.3	65.4	16.1	10.5	-31.7
United States	16.0	11.9	33.0	39.1	3077.3	-5.5
	21.1	17.4	42.5	19.0	1921.3	-37.6

Values were calculated as in Jacobson and Delucchi (2011) using EIA (2012d) end-use demand data. The U.S. population was 308,745,538 in 2010 and is projected to be 363,584,000 in 2030 and 399,803,000 in 2050 (USCB, 2013), giving U.S. population growth as 29.5% from 2010 to 2050.

In 2010, U.S. all-purpose, end-use power demand was ~2.37 TW (terawatts, or trillion watts). Of this, 0.43 TW (18.1%) was electric power demand. End-use power excludes losses incurred during production and transmission of the power. If the U.S. follows the business-as-usual (BAU) trajectory of the current energy infrastructure, all-purpose end-use demand is expected to grow to 2.79 TW in 2030 and 3.08 TW in 2050 (Table 1).

A conversion to WWS by 2050 is calculated here to reduce U.S. end-use power demand and the power required to meet that demand by ~37.6%. About 5.5 percentage points of this reduction is due to modest energy-conservation measures and another relatively small portion is due to the fact that conversion to WWS reduces the need for upstream coal, oil, and gas mining and processing of fuels, such as petroleum or uranium refining. The remaining and major reason for the reduction is that the use of electricity for heating and electric motors is more efficient than is fuel combustion for the same applications (Jacobson and Delucchi, 2011). Also, the use of WWS electricity to produce hydrogen for fuel cell vehicles, while less efficient than the use of WWS electricity to run BEVs, is more efficient and cleaner than is burning liquid fossil fuels for vehicles (Jacobson et al., 2005; Jacobson and Delucchi, 2011). Combusting electrolytic hydrogen is slightly less efficient but cleaner than is combusting fossil fuels for direct heating, and this is accounted for in Table 1.

The percent decrease in power demand upon conversion to WWS in Table 1 is greater in some states (e.g., Hawaii, Florida, New Jersey, California, and Arizona) than in others (e.g. Louisiana, Iowa, and Wyoming). The reason is that the transportation-energy share of the total in the states with the large reductions is greater than in those with the small reductions. Efficiency gains from electrifying transportation are greater than are efficiency gains from electrifying other sectors.

4. Numbers of Electric Power Generators Needed and Land-Use Implications

How many WWS power plants or devices are needed to power each state for all purposes assuming end use power requirements in Table 1 and accounting for electrical transmission and distribution losses? Table 2 provides a U.S. summary of the state-by-state future scenarios for 2050 that are given in Table 3. The specific mix of generators presented for each state in Table 3 is just one set of options. It is likely that, upon actual implementation, the number of each generator in this mix will shift - e.g., more power plant PV, less rooftop PV, etc. Table 2 indicates, that in the U.S. average, end-use power could be supplied by 31.0% onshore and 19.0% offshore wind, 29.6% utility-scale PV, 7.5% CSP, 4.7% residential rooftop PV, 3.9% commercial/government rooftop PV, 1.3% geothermal, 0.37% wave, 0.13% tidal, and 2.5% hydroelectric.

Table 2. 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. (2014c).

Energy Technology	Rated power of one plant or device (MW)	[a]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.	[b]Percent of U.S. land area for footprint of new plants / devices	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 [c]	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 [d]	0.1	3.89	495,593	0.36	4,938,184	0.04032	0.0000
Solar PV plant [d]	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 [e]						0.44	1.71

The number of devices is the end use power demand in 2050 from Table 1 multiplied by the fraction of power from the source and divided by the annual power output from each device, which equals the rated power multiplied by the annual capacity factor of the device and accounting for transmission and distribution losses. The capacity factor is determined for each device in each state as in Jacobson et al. (2014c). The state-by-state capacity factors for onshore wind turbines in 2050, accounting for transmission and distribution losses, were calculated from actual 2013 state installed capacity (DOE, 2014) and power output (EIA, 2014g), then assuming a 15% increase in capacity factor between 2013 and 2050 due to turbine efficiency improvements, and assuming a range +/-4%. The 2013 U.S. mean capacity factor calculated in this manner (after transmission and distribution losses) was 30.6%, and the 2050 U.S. mean capacity factor was 35.17%. The highest state capacity factor in 2050 is estimated to be 45.5%, for Oklahoma; the lowest, 20.5%, for onshore Alabama. Offshore wind turbines were assumed to be placed in locations with hub-height wind speeds of 8.5 m/s or higher (Dvorak et al., 2010), which corresponds to a capacity factor before transmission and distribution losses of ~42.5% for the same turbine. 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). Footprint and spacing areas are calculated from the spreadsheets in Jacobson et al. (2014c). Footprint is the area on the top surface of soil covered by an energy technology, thus does not include underground structures.

[a] Total end-use power demand in 2050 with 100% WWS is estimated from Table 1.

[b] Total land area for each state is given in Jacobson et al. (2014c).

[c] The average capacity factor for hydro is assumed to increase from its current value to 50% (see text). This can be achieved through retrofits and better management of the hydroelectric resource.

[d] 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. (2014c) 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. (2014c).

[e] 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.

Rooftop PV in Table 2 is divided into residential (5-kW systems on average) and commercial/government (100-kW systems on average). Rooftop PV can be placed on the existing rooftops or on elevated canopies above parking lots, highways, and structures without taking up additional undeveloped land. Table 4 and Section 5.2 provide a summary of projected 2050 rooftop areas by state usable for solar PV on residential and commercial/government buildings, carports, garages, parking structures, and parking lot canopies. The rooftop areas in Table 4 limit the distribution of installed rooftop PV for each state in Table 3. Utility-operated PV power plants are sized, on average, relatively small (50 MW) to allow them to be placed optimally in available locations. While utility-scale PV can operate in any state, CSP is assumed to be viable only in states with significant direct solar radiation.

Onshore wind is assumed to be viable primarily in states with good wind resources (Section 5.1). Offshore wind is assumed to be possible offshore any state with ocean or Great Lakes coastline, since such offshore resources are also cost effective (Section 5.1). Wind and solar are the only two sources of electric power that could power the whole U.S. independently on their own. Averaged over the U.S., wind (~50.0%) and solar (45.74%) are the largest generators of end-use electric power under these plans. The ratio of wind to solar end-use power is thus 1.09:1. Both are needed in roughly similar proportions on a large scale to help ensure reliability of the grid.

Under the roadmaps here, the 2050 installed capacity of hydroelectric, averaged over the U.S., is assumed to be virtually the same as in 2010, except for small growth in Alaska. However, existing dams in most states are assumed to run more efficiently for producing peaking power, thus the capacity factor of dams is assumed to increase (Section 5.4). Geothermal, wave, and tidal energy expansions are limited in each state by their potentials (Sections 5.3, 5.5, 5.6, respectively).

Table 3. Percent of 2050 state end-use power demand in a WWS world from Table 1 proposed here to be met by the given electric power generator. Power generation by each resource in each state is limited by resource availability, as discussed in Section 5.

State	Onshore wind	Offshore wind	Wave	Geoth-ermal	Hydro-electric	Tidal	Res PV	Comm/ gov PV	Utility PV	CSP
Alabama	5	10	0.08	0	4.69	0.01	4	2.55	63.67	10
Alaska	50	20	1	7	15	1	0.28	0.18	5.54	0
Arizona	19.15	0	0	2	4	0	1.85	13	30	30
Arkansas	43	0	0	0	3.20	0	4.70	3.80	35.30	10
California	25	10	0.50	5	3.50	0.50	8	6	26.50	15
Colorado	55	0	0	3	1	0	5	4.60	16.40	15
Connecticut	5	45	1	0	0.45	0	4	3.35	41.20	0
Delaware	5	65	1	0	0	0.50	5.40	3.85	19.25	0
Florida	5	14.93	1	0	0.03	0.04	15.5	10.8	42.70	10
Georgia	5	35	0.30	0	1.72	0.08	6	4.50	42.40	5
Hawaii	12	16	1	30	0.25	1	14	9	9.75	7
Idaho	35	0	0	15	11.94	0	4.80	3.80	19.46	10
Illinois	60	5	0	0	0.03	0	2.85	2.90	26.22	3
Indiana	50	0	0	0	0.06	0	2.45	2.20	42.79	2.50
Iowa	68	0	0	0	0.24	0	1.75	1.80	25.21	3
Kansas	70	0	0	0	0.01	0	3.20	3	13.79	10
Kentucky	8.45	0	0	0	1.25	0	3.20	2.10	80	5
Louisiana	0.65	60	0.40	0	0.10	0	1.55	1.40	30.90	5
Maine	35	35	1	0	5.83	1	6.40	2	13.77	0
Maryland	5	60	1	0	1	0.03	5.60	5	22.37	0
Massachusetts	13	55	1	0	1.24	0.06	3.90	3.30	22.50	0
Michigan	40	31	1	0	0.50	0	3.50	3.20	18.80	2
Minnesota	60	19	0	0	3	0	2.75	3	10.25	2
Mississippi	5	10	1	0	0	1	2.70	1.85	73.45	5
Missouri	60	0	0	0	0.91	0	5.10	4.40	24.59	5
Montana	35	0	0	9	17.76	0	3	2.30	22.94	10
Nebraska	65	0	0	0	0.88	0	2.50	2.40	19.22	10

Nevada	10	0	0	30	3.25	0	15.5	10.5	15	15.75
New Hampshire	40	20	1	0	4.30	0.50	4.95	3.50	25.75	0
New Jersey	10	55.5	0.80	0	0	0.10	3.54	2.80	27.26	0
New Mexico	50	0	0	10	0.33	0	6.20	4.20	13.27	16
New York	10	40	0.80	0	7.50	0.10	3.80	3.40	34.40	0
North Carolina	5	50	0.75	0	1.90	0.03	7.40	5	24.92	5
North Dakota	55	0	0	0	2.75	0	1.15	1.20	34.90	5
Ohio	45	10	0	0	0.08	0	3.20	3	35.72	3
Oklahoma	65	0	0	0	1.40	0	3.70	3	16.90	10
Oregon	32.5	15	1	5	21.39	0.05	5.20	2.80	12.06	5
Pennsylvania	20	3	1	0	0.65	0.85	3.40	2.35	68.75	0
Rhode Island	10	63	1	0	0	0.08	4.40	3.70	17.82	0
South Carolina	5	50	1	0	2.40	0.30	4.40	3	27.60	6.30
South Dakota	61	0	0	0	10.5	0	2.10	2.20	14.20	10
Tennessee	8	0	0	0	3.30	0	3.90	2.50	75.30	7
Texas	50	13.9	0.10	0.50	0.10	0	3.80	3.30	14.30	14
Utah	40	0	0	8	0.75	0	5.30	5.10	25.85	15
Vermont	26	0	0	0	50	0	4.20	2.80	17	0
Virginia	10	50	0.50	0	0.95	0.05	4.80	3.90	24.80	5
Washington	35	13	0.50	0.65	26.4	0.30	3.95	2.10	18.10	0
West Virginia	30	0	0	0	0.40	1	3	2.20	61.40	2
Wisconsin	45	30	0	0	0.75	0	3.30	2.90	16.05	2
Wyoming	65	0	0	1	1.47	0	1.35	1	20.18	10
United States	30.98	18.99	0.37	1.29	2.46	0.13	4.73	3.89	29.62	7.54

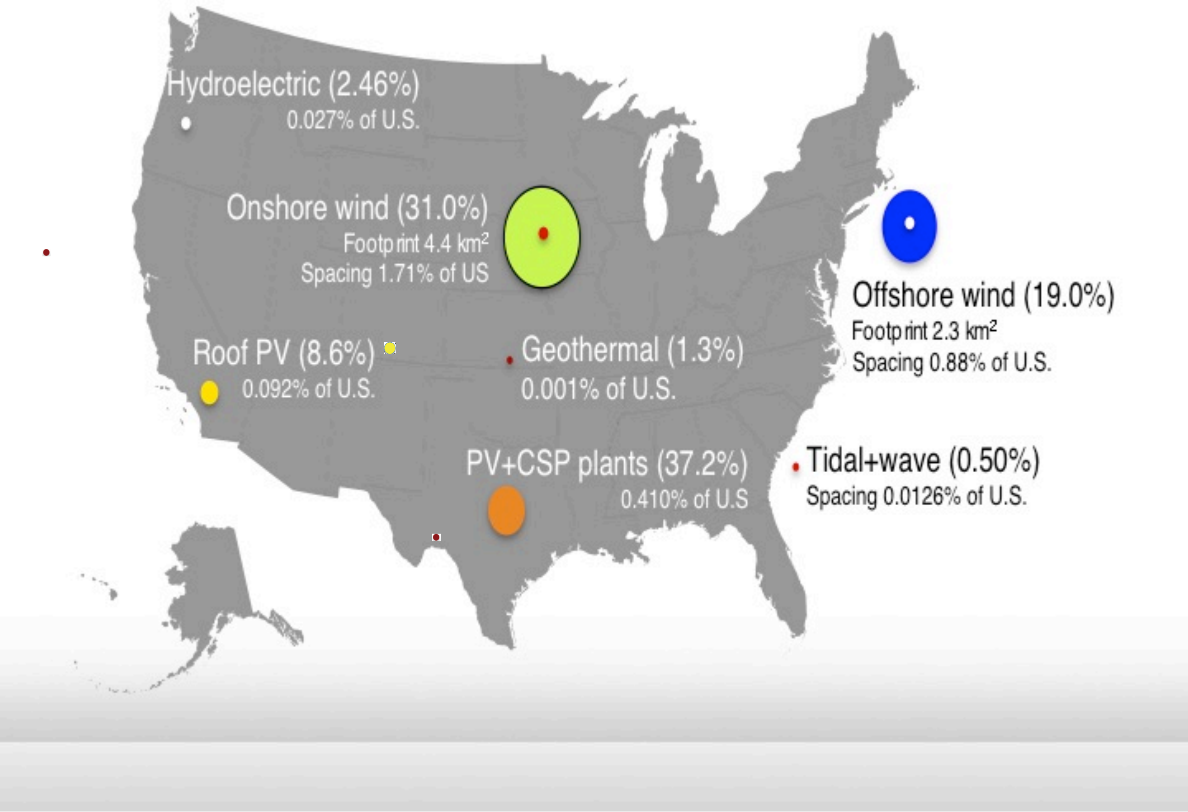
Transmission for offshore wind, wave, and tidal power will be under water and out of sight. Transmission within and near onshore wind, solar, geothermal, and hydroelectric farms or plants is usually underground. Short- and long-distance transmission offsite for all generators will be along existing pathways to the greatest extent possible, but with enhanced lines. Methods of increasing transmission capacity without requiring additional rights-of-way or increasing the footprint of transmission lines include the use of dynamic line rating equipment; high-temperature, low-sag conductors; voltage up-rating; and flexible AC transmission systems (e.g., Holman, 2011).

Figure 1 shows the additional footprint and spacing areas from Table 2 required to replace the entire U.S. all-purpose energy infrastructure with WWS by 2050. Footprint area is the physical area on the ground needed for each energy device. Spacing area is the area between some devices, such as wind, tidal, and wave turbines, needed to minimize interference of the wake of one turbine with downwind turbines.

Table 2 indicates that the total new land footprint required for the plans, averaged over the U.S. is ~0.44% of U.S. land area, mostly for solar PV power plants (rooftop solar does not take up new land). This does not account for the decrease in footprint from eliminating the current energy infrastructure, including the footprint for mining, transporting, and refining fossil fuels and uranium and for growing, transporting, and refining biofuels.

The only spacing over land needed for the WWS system is between onshore wind turbines and requires ~1.7% of U.S. land. The footprint associated with the spacing is trivial, and the spacing area can be used for multiple purposes, such as agricultural land, grazing land, and open space. Landowners can thus derive income, not only from the wind turbines on the land, but also from farming around the turbines.

Figure 1. Additional spacing and footprint areas required, from Table 2, to repower the U.S. state-by-state for all purposes in 2050. The dots do not indicate the actual location of energy farms. For wind, the small dot in the middle is footprint on the ground or water (not to scale) and the green or blue is space between turbines that can be used for multiple purposes. For others, footprint and spacing areas are mostly the same (except tidal and wave, where only spacing is shown). For rooftop PV, the dot represents the rooftop area needed.



5. Resource Availability

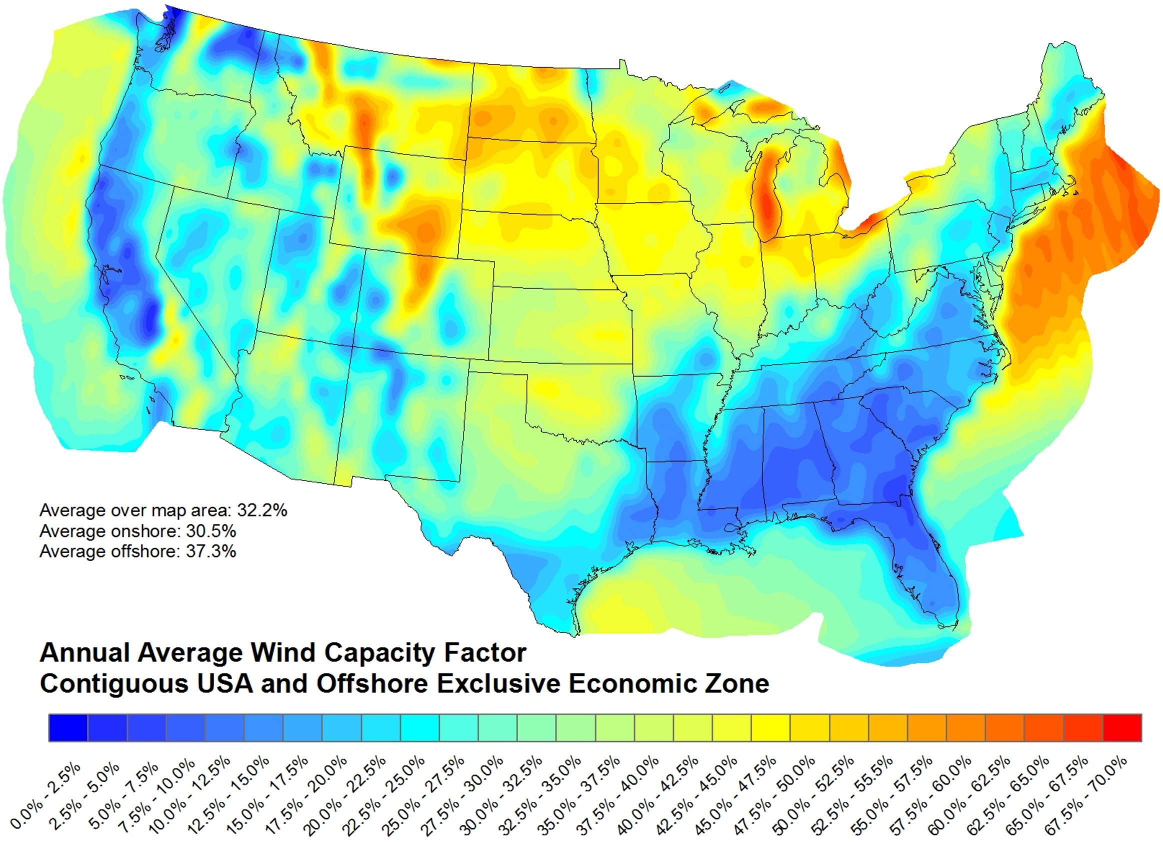
The United States has more wind, solar, geothermal, and hydroelectric resources than is needed to supply the country's energy for all purposes in 2050. In this section, U.S. wind, solar, geothermal, hydroelectric, tidal, and wave resources are examined.

5.1. Wind

Figure 2 shows three-dimensional computer model estimates, derived for this study, of the U.S. annually averaged capacity factor of wind turbines if they were installed onshore and offshore. The calculations were performed assuming a RePower 5 MW turbine with a 126-m diameter rotor. Results were obtained for a hub height of 100-m above the topographical surface. Spacing areas of 4x7 rotor diameters were used for onshore turbines and 5x10 diameters for offshore turbines.

Results suggest that the U.S. mean onshore capacity factor may be 30.5% and offshore, 37.3% (Figure 2). 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. Table 2 indicates that the 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% (Table 2, footnote). Figure 2 suggests that much more land and ocean areas with these respective capacity factors or higher are available than are needed for the plans.

Figure 2. 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.

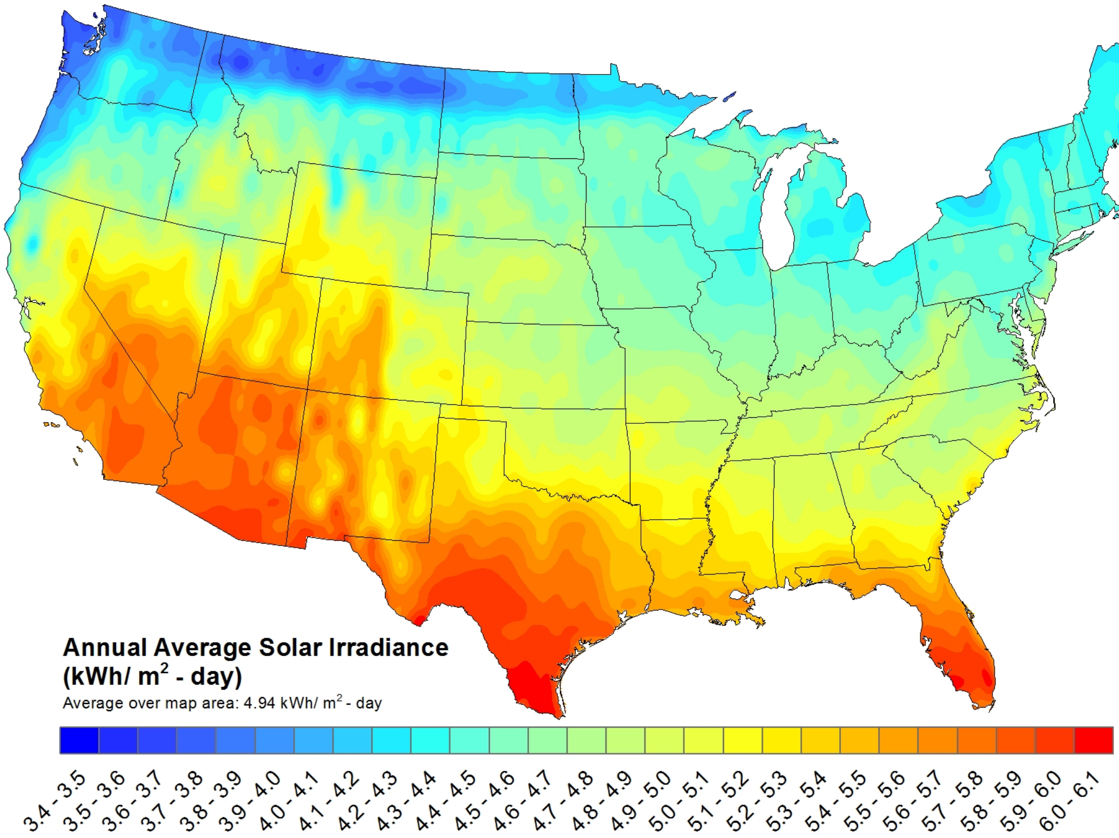


5.2. Solar

Figure 3 shows annually averaged modeled solar resources in the U.S., accounting for sun angles, day/night, and clouds. 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 3 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 here.

Figure 3. Modeled 2013 annual downward direct plus diffuse solar radiation at the surface (kWh/m^2/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).



The proposed 2050 installed capacity of solar PV on rooftops in Table 2 is limited by usable rooftop areas. Rooftops include those on residential and commercial/governmental buildings as well as on garages, carports, parking lots, and parking structures associated with each. Commercial/governmental buildings include all non-residential buildings except manufacturing, industrial, and military buildings. Commercial buildings include schools. Jacobson et al. (2014a, Supplemental Information) describe in detail how rooftop areas and potential were calculated for California. We describe briefly this methodology here, which was replicated for each U.S. state.

Each state's potential installed capacity of rooftop PV in 2050 equals the potential alternating-current (AC) generation from rooftop PV in 2050 in the state divided by the PV capacity factor in 2050. This calculation is performed here for each state for four situations: residential and commercial/government rooftop PV systems in each warm and cool climate zones.

The potential AC generation from rooftop PV in 2050 equals the solar power incident on potential rooftop PV-panel area in 2050 multiplied by the average PV module conversion efficiency in 2050, which equals the efficiency in 2012 (14.5%; DOE, 2012b) multiplied by an assumed 0.85%/year increase in efficiency (from projections in DOE, 2012b).

The solar power incident on potential rooftop PV panel area in 2050 equals the potential in 2012 multiplied by the increase in the potential rooftop area for PV between 2012 and 2050. We assume that the area of residential rooftops (excluding garages and carports) increases at the projected rate of population increase in each state, and that residential parking rooftop areas increases at a slightly higher rate, 0.84%/year, to account for the covering of previously-uncovered parking spaces specifically to install PV. We assume that the area of commercial/government rooftops (excluding parking lots) increases at the product of the rate of increase in population (see above) and the rate of increase in the ratio of commercial building area to population (0.08%/year; Kavalec and Gorin, 2009).

The solar irradiance incident on potential rooftop-panel area in 2012 equals the average year-round surface-incident solar radiation from Figure 3 (e.g., for California, 245 W/m^2 in warm zones and 215 W/m^2 in cool zones) multiplied by the potential rooftop PV panel area in 2012. The potential rooftop PV panel area in 2012 equals the total rooftop area multiplied by the fraction of the area that is suitable for PV and the fraction of available area occupied by the PV panels (80%; Navigant Consulting, 2007). We assume that 27% (warm zones) or 22% (cool zones) of residential rooftop area is suitable for PV and 60% (warm zones) or 65% (cool zones) of commercial/government roof area is suitable (Navigant Consulting, 2007). We assume that 10% less of the residential garage or carport area than of the house rooftop area is suitable for solar because garage or carport roofs are on the first story and hence more subject to shading.

The total residential rooftop area in 2012 is estimated using data on housing units by type of structure (USCB, 2014b), our assumptions about the number of housing units per rooftop by type of residential structure, the number of covered parking spaces per housing unit (based in part on data from the American Housing Survey; USCB, 2014a), the percentage of roofs that are pitched (92%, excluding garages, which is needed to get from "flat" rooftop area to actual rooftop area; Navigant Consulting, 2007), and the fraction of pitched roofs by type of covered parking space (our assumptions). See the spreadsheet in Jacobson et al. (2014c) for details.

The total commercial/government rooftop area in 2012 is based on the commercial/government floor space per person in 2012 (Kavalec and Gorin, 2009), each state's population in 2012, the ratio of roof area to floor space (EIA, 2008), and assumptions regarding the fraction of buildings with pitched roofs (EIA, 2008). We then assume that the area of parking-lot roofs built for PV is 10% of the commercial rooftop area. See the spreadsheet in Jacobson et al. (2014c) for details.

Jacobson et al. (2014a, Supplementary Information) described in detail the calculation of rooftop PV capacity factor in California for four situations (residential-warm, residential-cool, commercial/government-warm, and commercial/government-cool). This calculation was repeated here for each of the 50 states. The calculation accounted for solar insolation available to each state, degradation of solar panels over time, technology improvements over time, and DC to AC power conversion losses.

With these methods, we estimate that, in 2050, residential rooftop areas (including garages and carports) of 3,200 km^2 in the U.S. could support 660 GW of installed power. The plans here propose to install 97% of this potential. In 2050, commercial/government rooftop areas (including parking lots and parking structures) are estimated at 2,386 km^2, supporting 505 GW of installed power. The state plans here propose to cover 98% of installable power.

Table 4. 2050 rooftop areas, fraction of rooftop areas covered with proposed PV installations, and installed rooftop PV, for both residential and commercial/government buildings, by state in the U.S.

State	2050 Residential rooftop area (km^2)	2050 Technical potential residential rooftop PV (MW)	2050 Proposed installed PV on residences (MW)	2050 Percent of residential roofs covered with installations proposed here	2050 Commercial/government rooftop area (km^2)	2050 Technical potential comm./govt. rooftop PV (MW)	2050 Proposed installed PV power on comm./govt. rooftops (MW)	2050 Percent of comm./govt. roofs covered with installations proposed here
Alabama	59.7	10,130	10,006	99%	35.4	6,150	6,025	98%
Alaska	7.0	760	740	97%	4.2	460	450	98%
Arizona	7.1	3,520	3,447	98%	46.9	23,210	22,875	99%
Arkansas	36.7	7,090	6,881	97%	27.0	5,330	5,255	99%
California	336.1	83,150	76,237	92%	220.6	55,330	54,006	98%
Colorado	48.8	11,190	10,801	97%	40.6	9,440	9,386	99%
Connecticut	32.2	4,640	4,609	99%	25.1	3,690	3,646	99%
Delaware	10.9	1,940	1,916	99%	7.3	1,320	1,290	98%
Florida	229.1	85,950	83,795	97%	148.4	55,750	55,147	99%
Georgia	108.9	25,760	25,373	98%	76.9	18,450	17,974	97%
Hawaii	12.7	3,260	3,115	96%	7.5	1,950	1,891	97%
Idaho	16.2	4,030	3,996	99%	12.2	3,070	2,988	97%
Illinois	116.3	17,220	16,895	98%	110.6	16,770	16,238	97%
Indiana	65.6	10,500	10,387	99%	54.8	8,960	8,809	98%
Iowa	31.2	4,430	4,319	97%	29.4	4,260	4,196	98%
Kansas	32.1	5,220	5,160	99%	28.1	4,680	4,569	98%
Kentucky	52.7	8,270	8,057	97%	32.3	5,200	4,994	96%
Louisiana	54.2	9,910	9,630	97%	44.6	8,350	8,216	98%
Maine	32.2	4,740	4,661	98%	9.4	1,410	1,376	98%
Maryland	60.5	11,550	11,210	97%	49.0	9,530	9,454	99%
Massachusetts	58.6	8,560	8,513	99%	46.4	6,930	6,803	98%

Michigan	105.0	14,970	14,820	99%	89.0	12,980	12,798	99%
Minnesota	52.9	9,280	9,117	98%	54.6	9,740	9,394	96%
Mississippi	35.5	4,950	4,892	99%	22.6	3,230	3,166	98%
Missouri	72.9	12,260	12,025	98%	58.0	9,980	9,799	98%
Montana	11.6	1,880	1,843	98%	8.2	1,350	1,335	99%
Nebraska	20.5	3,140	3,104	99%	18.0	2,830	2,814	99%
Nevada	29.4	15,120	14,739	97%	18.8	9,600	9,430	98%
New Hampshire	13.9	2,480	2,451	99%	9.3	1,680	1,637	97%
New Jersey	83.1	12,730	12,649	99%	60.7	9,520	9,450	99%
New Mexico	24.7	5,070	5,044	99%	15.7	3,300	3,227	98%
New York	165.2	20,140	19,914	99%	135.0	16,940	16,829	99%
North Carolina	119.2	28,340	27,897	98%	74.6	17,950	17,803	99%
North Dakota	7.2	940	907	96%	6.8	920	894	97%
Ohio	117.0	16,960	16,511	97%	101.0	15,000	14,620	97%
Oklahoma	46.2	8,150	7,901	97%	34.8	6,270	6,051	97%
Oregon	43.5	8,590	8,419	98%	21.6	4,330	4,282	99%
Pennsylvania	136.4	18,870	18,731	99%	87.9	12,410	12,228	99%
Rhode Island	9.9	1,460	1,442	99%	7.8	1,180	1,145	97%
South Carolina	58.4	9,220	9,137	99%	36.8	5,950	5,884	99%
South Dakota	8.5	1,290	1,256	97%	8.3	1,280	1,243	97%
Tennessee	76.6	12,020	11,821	98%	45.9	7,370	7,157	97%
Texas	268.9	78,190	75,473	97%	216.9	63,550	61,906	97%
Utah	23.1	6,360	6,295	99%	20.9	5,810	5,722	98%
Vermont	7.5	1,110	1,071	97%	4.5	680	675	99%
Virginia	88.1	17,400	17,026	98%	65.8	13,190	13,066	99%
Washington	73.6	14,050	13,918	99%	37.2	7,180	6,989	97%
West Virginia	24.3	3,140	3,017	96%	16.1	2,140	2,090	98%
Wisconsin	59.5	9,310	9,215	99%	48.3	7,710	7,649	99%
Wyoming	6.3	1,050	1,035	99%	4.5	760	724	95%
United States	3,197.6	660,290	641,416	97%	2,386	505,070	495,593	98%

5.3. 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 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%) (USGS, 2008). 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. Such electricity use for heat pumps is accounted for in the numbers for Table 1.

The roadmaps here propose 24.8 GW of delivered existing plus new electric power by geothermal in 2050, less than the sum of identified and undiscovered resources and much less than the enhanced recovery resources. The proposed electric power from geothermal is limited to the 13 states that known resources exist plus Texas, where recent studies show several potential sites for geothermal.

5.4. Hydroelectric

In 2010, conventional (small and large) hydroelectric power provided 29.7 GW (260,203 GWh/yr) of U.S. electric power, or 6.3% of the U.S. electric power supply (EIA, 2012e). The installed conventional hydroelectric capacity was 78.825 GW (EIA, 2012e), giving the capacity factor of conventional hydro as 37.7% in 2010. States that year with installed conventional hydro included Washington State (21.181 GW installed capacity), California (10,141), Oregon (8,425), New York (4,314), Alabama (3,272), Arizona (2,720), Montana (2,705), Idaho (2,704), Tennessee (2,624), Georgia (2,052), North Carolina (1,956), South Dakota (1,594), Arkansas (1,341), South Carolina (1,340), Nevada (1,051), Virginia (866), Oklahoma (858), Kentucky (824), Pennsylvania (747), Maine (738), Texas (689), Colorado (662), Maryland (590), Missouri (564), North Dakota (508), Wisconsin (492), New Hampshire (489), Alaska (414), Vermont (324), Wyoming (307), West Virginia (285), Nebraska (278), Massachusetts (262), Utah (255), Michigan (237), Minnesota (193), Louisiana (192), Iowa (144), Connecticut (122), Ohio (101), New Mexico (82), Indiana (60), Florida (55), Illinois (34), Hawaii (24), New Jersey (4), Kansas (3), and Rhode Island (3) (EIA, 2012e).

In addition, 23 U.S. states receive an estimated 5.1 GW of delivered hydroelectric power from Canada. Assuming a capacity factor of 50%, Canadian hydro currently provides ~10.2 GW worth of installed capacity to the U.S. This is included as part of existing hydro capacity here to give a total existing capacity in the U.S. in Table 2 of 89.03 GW.

The U.S. also has 22.2 GW of installed pumped hydroelectric storage in 18 states, led by California (3.81), Virginia (3.24 GW), and South Carolina (2.67 GW) (EIA, 2012e). As of April 1, 2014, licenses for another 2.74 GW of pumped hydro were pending in 3 states and preliminary permits for another 41.3 GW were pending in 19 states (FERC, 2014). A total of 28 states have current or pending projects. With pumped hydro, water flows between two reservoirs, a higher and lower one. Water is pumped to the higher reservoir at times of low peak demand and cost and used to generate electricity at times of high peak demand and cost. Pumped storage uses slightly more electricity than it generates, so it is not a "source" of electric power; instead it allows peak power demand to be met reliably and cost-effectively, which will be important in a 100% WWS world.

Under the plan proposed here, conventional hydro will supply 47.26 GW of delivered power, or 2.46% (Table 2) 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 (Table 2). 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.

Alternatively, additional hydroelectric capacity can be obtained by powering non-powered dams. The U.S. has over 2,500 dams that provide the 78.8 GW of installed conventional power and 22.2 GW of installed pumped-storage hydroelectric power. In addition, the U.S. has over 80,000 non-powered dams. However, among these, only a few can feasibly be repowered. DOE (2012a) estimates 12 GW of potential capacity from non-powered dams in the contiguous U.S., with two-thirds from 100 dams, but with potential in every state. Over 80% of the top 100 dams in terms of capacity are navigation locks on the Ohio, Mississippi, Alabama, and Arkansas Rivers and their tributaries. Illinois, Kentucky, and Arkansas each have over 1 GW of potential. Alabama, Louisiana, Pennsylvania, and Texas each have 0.5-1 GW of potential. Because the costs and environmental impacts of such dams have already been incurred, adding electricity generation to these dams is less expensive and faster than building a new dam with hydroelectric capacity.

In addition, DOE (2006) estimates that the U.S. has an additional low power and small hydroelectric potential of 30-100 GW of delivered power. The states with the most additional low and small hydroelectric potential are Alaska, Washington State, California, Idaho, Oregon, and Montana. However, 33 states can more than double their small hydroelectric potential and 41 can increase it by more than 50%.

5.5. Tidal

Tidal (or ocean current) is proposed to comprise about 0.13% of U.S. total power in 2050 (Table 2). The U.S. currently has the potential to generate 50.8 GW (445 TWh/yr) of delivered power from tidal streams (Georgia Tech Research Corporation, 2011). States with the greatest 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.

5.6. 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 2). 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 (EPRI, 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.

6. Matching Electric Power Supply with Demand

A question integral to this study is whether conversion to 100% WWS for electricity combined with enhanced electric loads due to electrification of transportation, heating and cooling, and industry can result in a stable electric power supply in each state. This section discusses several ways this can be accomplished.

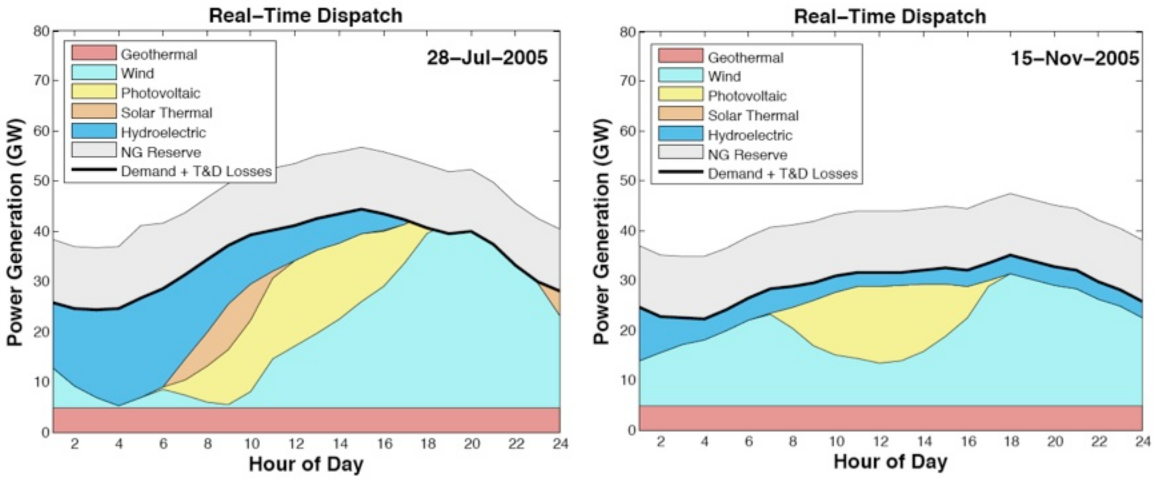
6.A. Combining WWS Resources as a Bundled Set of Resources

Several studies have examined whether up to 100% penetrations of WWS resources could be used reliably to match power demand (e.g., Jacobson and Delucchi, 2009; Mason et al., 2010; Hart and Jacobson, 2011, 2012; Connolly et al., 2011; Mathiesen et al., 2011; Elliston et al., 2012; NREL, 2012; Rasmussen et al., 2012; Budischak et al., 2013; Mai et al., 2013).

Here, we do not model the reliability of an optimized future grid in each state but discuss a recent optimization study in which 100% WWS in the California grid was modeled for two years then discuss additional methods of matching electric power demand with supply. Hart and Jacobson (2011) used a stochastic optimization model of system operation combined with a deterministic renewable portfolio-planning module to simulate the impact of a 100% WWS penetration for California every hour of 2005 and 2006. They assumed near-current hydroelectric and geothermal but increased geographically dispersed time-dependent wind, solar PV, and CSP with 3-hour storage. They constrained the system to a loss of load of no more than 1 day in 10 years and used both meteorological and load forecasts to reduce reserve requirements. They found that, under these conditions, 99.8% of delivered electricity could be produced carbon-free with WWS during 2005-2006 (e.g., Figure 4 for two days).

The result of Hart and Jacobson (2011) suggests that, for California, a large part of the intermittency problem of wind and solar can be addressed not only by combining the two, but also by using hydroelectric and CSP with 3-hour storage to fill in gaps. The remaining differences between supply and demand can likely be addressed with the methods discussed in Sections 6.B. through 6.G. The results of Hart and Jacobson (2011) are supported further by those of Budischak et al. (2013), who modeled the PJM Interconnection in the eastern U.S. over four years and found that up to 99.9% of delivered electricity could be produced carbon-free with WWS resources. In sum, a complete and optimized WWS system in many states should require no fossil backup but will benefit from hydroelectric and/or CSP storage.

Figure 4. Matching California electricity demand plus transmission/distribution losses (black line) with 100% renewable supply based on a least-cost optimization calculation for two days in 2005.



Notes: System capacities are 73.5 GW of wind, 26.4 GW of CSP, 28.2 GW of photovoltaics, 4.8 GW of geothermal, 20.8 GW of hydroelectric, and 24.8 GW of natural gas. Transmission and distribution losses are 7% of the demand. The least-cost optimization accounts for the day-ahead forecast of hourly resources, carbon emissions, wind curtailment, and 8-hour thermal storage at CSP facilities, allowing for the nighttime production of energy by CSP. The hydroelectric supply is based on historical reservoir discharge data and currently imported generation from the Pacific Northwest. The wind and solar supplies were obtained by aggregating hourly wind and solar power at several sites in California estimated from wind speed and solar irradiance data for those hours applied to a specific turbine power curve, a specific concentrated solar plant configuration (parabolic trough collectors on single-axis trackers), and specific rooftop PV characteristics. The geothermal supply was increased over 2005 but limited by California's developable resources. Natural gas capacity (grey) is a reserve for backup when needed and was not actually needed during the two simulation days. Source: Hart and Jacobson (2011).

6.B. Using Demand-Response Grid Management to Adjust Demand to Supply

Demand-response grid management involves giving financial incentives to electricity users and developing appropriate system controls to shift times of certain electricity uses, called flexible loads, to times when more energy is available. Flexible loads are electricity demands that do not require power in an unchangeable minute-by-minute pattern, but instead can be supplied in adjustable patterns over several hours. For example, electricity demands for a wastewater treatment plant and for charging BEVs are flexible loads. Electricity demands that cannot be shifted conveniently, such as electricity use for computers and lighting, are inflexible loads. With demand-response, a utility may establish an agreement with (for example) a flexible load wastewater treatment plant for the plant to use electricity during only certain hours of the day in exchange for a better electricity rate. In this way, the utility can shift the time of demand to a time when more supply is available. Similarly, the demand for electricity for BEVs is a flexible load because such vehicles are generally charged at night, and it is not critical which hours of the night the electricity is supplied as long as the full power is provided sometime during the night. In this case, a utility can contract with users for the utility to provide electricity for the BEV when wind is most available and reduce the power supplied when it is least available. Utility customers would sign up their BEVs under a plan by which the utility controlled the supply of power to the vehicles (primarily but not necessarily only at night) in exchange for a lower electricity rate.

6.C. Oversizing WWS to Match Demand and Provide Hydrogen and District Heat

Oversizing the peak capacity of wind and solar installations 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 (albeit at some cost). The additional energy available when WWS generation exceeds demand can be used to produce district heat for water and air and hydrogen (a storage fuel) for heating and transportation. Denmark, for example, currently uses excess wind energy for district heating using heat pumps and thermal stores (e.g., Elsman, 2009). In the case of hydrogen, it 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. Curtailing wastes energy; thus, reducing curtailment and using the energy for other purposes should reduce overall system costs. Hydrogen for transportation can be produced at vehicle fueling stations by transmitting the excess electric power directly to those stations using existing or expanded transmission lines. Alternatively, hydrogen can be produced at a central location, then transfer it by pipeline to fueling stations. However, transmission via electricity can use more of the existing infrastructure.

6.D. Using Weather Forecasts to Plan for and Reduce Backup Requirements

Forecasting the weather (winds, sunlight, waves, tides, and precipitation) improves the ability of grid operators to appropriately schedule backup power for when a variable energy source might produce less than anticipated. Good forecast accuracy can also reduce the use of peaker plants (which can be rapidly turned on and ramped to meet demand, but which emit more pollution during transient operation) and inefficient part-loading of plants to provide spinning reserves, reducing the overall carbon emissions of the system compared with using natural gas as backup (Hart and Jacobson, 2011; 2012). The state plans proposed here use hydroelectric and stored CSP, among other options, but not natural gas, to fill in gaps in supply. Better forecasting will improve the utilization of hydroelectric resources. Forecasting is done with both numerical weather prediction models, the best of which can produce usable predictions 1 to 4 days in advance, and with statistical models based on local measurements and historical behavior. The use of forecasting reduces uncertainty and makes scheduling more dependable, thus reducing the need for contingent generation capacity, greater storage, or more load shifting.

6.E. Storing Electric Power

Another method of helping to match power demand with supply is to store excess energy in pumped hydroelectric storage, a thermal storage medium (such as a molten nitrate salt with CSP or soil), hydrogen for use in fuel cells or high-temperature processes, batteries, compressed air (e.g., in underground caverns or turbine nacelles), and flywheels.

As discussed in Section 5.4, the U.S. currently has ~78.8 GW of installed hydroelectric power plus another 22.2 GW of installed pumped storage and 44.0 GW of pending licenses and preliminary permits for more pumped storage. Summing conventional capacity plus current and pending pumped storage capacity gives an upper limit of 145 GW of peak hydro output at a given time, or 7.5% of the 2050 all-purpose annual-average U.S. end-use power demand.

As part of the plan, 7.54% of 2050 all-purpose power demand will be met by CSP (Table 2). If the size of CSP storage equals the rated power of the steam turbines used to generate electricity for CSP, CSP-storage could provide 7.54% of the 2050 all-purpose annual-average U.S. end-use power demand at night and when no wind or other WWS resources were available.

In addition, storing energy in or extracting it from soil for use in buildings can reduce building energy use, transmission infrastructure needs, and energy-system costs further. Some methods of reducing building energy use and taking advantage of storage include (1) extracting heat in the summer and cold in the winter from the air and from solar devices and storing it in the soil for use in the opposite season (e.g., Drake Landing, 2012), (2) recovering heat from air conditioning systems and using it to heat water or air in the same or other buildings, (3) extracting heat (or cold) from the ground, air, or water with heat pumps and using it immediately to heat (or cool) air or water, and (4) using solar energy to generate electricity through PV panels, to recover heat from water used to cool the panels, and to heat water directly for domestic use (e.g., Tolmie et al., 2012)

Storage in hydrogen is particularly advantageous because significant hydrogen will be needed in a global WWS energy economy for use in fuel cells, aircraft, and high-temperature industrial processes. Hydrogen would be produced by electrolysis where the electricity originates from WWS sources. Since hydrogen would be produced primarily when electricity supply exceeds demand, hydrogen production would avoid the lost revenues of curtailing WWS resources.

Locations of compressed air storage are limited but some exist. For example, one site in eastern Washington State may provide 40 days of continuous storage capacity, which could provide over 400 hours of generation at 207 MW (PNNL, 2013).

Table 5 provides current and estimated future costs of several existing storage technologies. Pumped hydroelectric storage, sodium sulfur batteries, and flywheel storage are currently cost-competitive with conventional gas-combustion turbines for intra-hour energy service. Lithium ion batteries and redox flow technologies are forecast to be cost-competitive by 2020.

Table 5. Approximate lifecycle cost of energy storage technologies for intra-hour energy service (2011 U.S. million dollars/MW). Assessment includes capital, O&M, emissions, and fuel costs (PNNL, 2012).

Energy Storage Technology	2011	2020
Combustion turbines	3.6	3.5
Pumped hydroelectric power	3.3	3.4
Sodium sulfur batteries	2	1.4
Lithium ion batteries	4	2.2
Redox flow batteries	4.5	3
Flywheel	3.1	1.7

6.F. Vehicle-to-Grid

An additional method of better matching power supply with demand is to store electric power in the batteries of BEVs, and then to withdraw such power when needed to supply electricity back to the grid. This concept is referred to as vehicle-to-grid (V2G) (Kempton and Tomic, 2005a). The utility would enter into a contract with each BEV owner to allow electricity transfers back to the grid any time during a specified period agreed upon by the owner in exchange for a lower electricity price. V2G has the potential to wear down batteries faster, but Kempton and Tomic (2005b) suggests that only 3.2 percent of U.S. light-duty vehicles, if all converted to BEVs, would need to be under contract for V2G vehicles to smooth out U.S. electricity demand if 50 percent of demand were supplied by wind.

6.G. Increasing the Use of Distributed Energy Resources

Distributed Energy Resources (DERs), such as rooftop PV, wind turbines, and distributed energy storage systems are among the fastest growing renewable energy resources worldwide (Arghandeh and Broadwater, 2012). DERs are usually located near sites of end-used power demand. Therefore, they can improve reliability and flexibility of the grid by providing energy during outages or failures. Moreover, utilities or DER owners can take advantage of load shedding in case of higher electricity prices at peak hours. DERs with intelligent control system can also reduce loading on the grid components during peak hours, decreasing stress on the grid and thereby allowing the utility to delay equipment upgrades and to decrease pre-mature aging in network components. Voltage, frequency and load control can be embedded into the power-electronic interface of DER units. The economic befit of DERs operation in an optimal way can outweigh or partly compensate the installation cost of such resources in distribution and transmission networks. The service availability, reliability enhancement and peak shaving in addition to the revenue attainable by market-based scheduling of DERs are among potential economic attraction of renewable sources with control system for utilities (Arghandeh et al., 2012). There are three different approaches for DER optimal operation: 1) control of the renewable energy resource (Jahangiri and Aliprantis, 2013) , 2) control of renewable source combined with energy storage (Arghandeh et al., 2012), and 3) a combination of renewable source, energy storage and load control (Saber and Venayagamoorthy, 2010). The third one has more flexibility than other approaches.

7. Costs of Electric Power Generation

In this section, current and future full social costs (including capital, land, operating, maintenance, storage, fuel, transmission, and externality costs) of WWS electric power generators versus non-WWS conventional fuel generators are estimated. Because our estimates are based on current cost data and trend projections for individual generator types and do not account for interactions among energy generators, major end uses, or transmission and storage systems (e.g., wind and solar power in combination with heat pumps and electric vehicles; e.g., Mathiesen, 2009); the estimates are only a rough approximation of costs in a future optimized renewable energy system.

Table 6 presents 2013 and 2030 U.S. averaged estimates of fully-annualized levelized costs of electric power generation for WWS technologies assuming 1 U.S. ¢/kWh for standard (but not extra-long-distance) transmission for all technologies except commercial and residential solar PV (to which no transmission cost is assigned), and excluding distribution costs. The future estimates are "approximate" not only because of normal uncertainty in estimating technology costs, but also because of uncertainty in the design and optimization of a future electric power system.

Table 6. Approximate fully annualized, unsubsidized 2013 and 2030 U.S. averaged generation and short-distance transmission costs for WWS power (2013 U.S. ¢/kWh-delivered), including externality costs. Also shown are generation costs and externality costs of new non-WWS conventional fuels (nuclear, coal, and natural gas).

Energy Technology	2013*	2030*
Wind Onshore	4[a]-10.5[b]	≤4[a]
Wind Offshore	11.3[c]-16.4[b]	7[b]-10.9[c]
Wave	11.0-22.0[a]	4-11[a]
Geothermal	9.9-15.2[b]	5.5 -8.8[b]
Hydroelectric	4.0-6.0[d]	4[a]
CSP	13.5-17.4[b]	7 -8[a]
Solar Crystalline PV (Utility)	10.1-11.4[b]	4.5-7[f]
Solar PV (Commercial Rooftop)	14.9-20.4[b]	6.0-9.8[f]
Solar PV (Residential Rooftop)	17.8-24.3[e]	6.2-10[f]
Tidal	11.0-22.0[a]	5-7[a]
Weighted average WWS[g]	**11.3 (9.1-13.5)**	**6.1 (5.2-7.1)**
New conventional (plus externalities)[h]	**10.1 (9.8-10.5) [+5.3] =15.4 (15.1-15.8)**	**17.0 (16.3-17.6) [+5.7] =22.7 (22.0-23.3)**

*1 U.S. ¢/kWh for transmission was added to all technologies as in Delucchi and Jacobson (2011) except for distributed generation projects (i.e. commercial and residential solar PV). The externality cost of WWS technologies is <0.02 ¢/kWh (Jacobson et al., 2013).

a) Delucchi and Jacobson (2011)

b) Lazard (2013). Assumes system life of 20 years for solar PV, geothermal, onshore and offshore wind, and gas; and 40 years for CSP, nuclear, and coal. Assumes 8% interest for 60% of cost 40% equity at 12% cost.

c) Levitt et al. (2011)

d) REN21 (2010)

e) The residential PV LCOE is calculated by multiplying the Lazard (2013) commercial LCOE by the ratio of the residential-to-commercial PV $/Watt ($4.72/$3.96) from SEIA (2013).

f) Calculated using the method and assumptions for "Solar PV" in Table A.1d of Delucchi and Jacobson (2011), with adjustments as explained in the Supplemental information to Jacobson et al. (2014a).

g) The weighted-average WWS cost combines the 2050 distribution of WWS generators from Table 2 with the 2013 costs of energy from the present table.

h) See text for derivation of conventional-fuel private costs and Jacobson et al. (2013) for derivation of externality costs in 2013 and 2030.

Table 6 also shows the U.S.-averaged 2013 business (private) plus externality (social) delivered electricity cost of non-WWS conventional fuels (nuclear, coal, and natural gas). The 2013 cost was derived as follows. Lazard (2013) estimates the 2013 levelized cost of energy (LCOE) for nuclear, coal, and natural gas as 10.4, 10.5, and 7.5 U.S. ¢/kWh, respectively. EIA (2012b) similarly estimates the 2015 LCOEs for these generators as 111.4, 97.7, and 66.1 ¢/kWh, respectively. Summing the product of the 2013 electric power generation (TWh) from nuclear, coal, and gas and the minimum of the Lazard (2013) and EIA (2012b) LCOEs for each respective generator, over all generators in a state, then dividing the result by the sum of state power produced by the generators and adding 1 ¢/kWh for transmission gives the Table 6 low estimate of the blended private LCOE of 2013 conventional generation. The same approach is taken to calculate the high value.

The 2030 U.S. average private electricity cost of non-WWS conventional fuels in Table 6 was taken as a weighted average (by electricity production) of each state's 2030 estimated cost. The 2030 cost in each state was assumed to increase from the 2013 cost at the same rate as the increase in the state's electricity price from 2000-2012. The resulting average U.S. electricity price increase from 2000-2012 was 3.08%/year (EIA, 2012a).

Jacobson et al. (2013) shows the derivation of the externality costs resulting from coal and natural gas electric power generation shown in Table 6. Such costs arise due to air pollution morbidity and mortality and global warming damage (e.g. coastline loss, agricultural and fishery losses, human heat stress mortality and increases in severe weather) caused by these fossil fuels.

Table 6 indicates that 2013 costs of electricity from onshore wind and hydroelectricity are similar to or less than those of typical new conventional generators even when externality (social) costs of the conventional technologies are ignored. When externality costs are included, these WWS technologies cost less than conventional technologies in 2013. Solar power presently is more expensive than is conventional power, but its costs have been declining.

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.

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.

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.

The estimates in Table 6 include the cost of local transmission. However, many 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 2, 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).

Table 7 provides the mean value of the 2013 and 2030 LCOEs for conventional fuels using the method described for Table 6 as well as the mean value of the LCOE of WWS fuels in 2030 by state, derived as described in the footnote to Table 6. Taking the difference between the state-specific conventional fuel and WWS LCOEs in 2030, multiplying by the end-use WWS energy consumption by each state in 2050 from Table 1 and dividing by each state's population gives the energy cost savings per person in 2050 (assuming energy cost differences between 2030 and 2050 are roughly similar) in Table 7. Table 7 also shows health and climate cost savings per person in 2050 and the total energy, health, and climate cost savings per person. Because the fuel costs of fossil fuels rise over time, whereas the fuel costs of WWS energy resources are zero, WWS energy in 2050 will save the average U.S. consumer $4,500/person/yr compared with the 2050 energy cost of fossil fuels to perform the same work. Health and climate cost savings due to WWS will be another $3,100/person/year, giving a total cost savings of $7,600/person/year due to WWS.

Table 7. Mean values of the levelized cost of energy (LCOE) for conventional fuels in 2013 and 2030 and for WWS fuels in 2030. The LCOEs do not include externality costs. The differences between the 2030 values are used to calculate energy cost savings per person per year in each state. Health and climate cost savings are derived from data in Section 8.

State	[a](a) 2013 LCOE of conventional fuels (¢/kWh)	[b](b) 2030 LCOE of conventional fuels (¢/kWh)	[c](c) 2030 LCOE of WWS (¢/kWh)	[d](d) 2030-50 Energy cost savings per person per year ($/person/yr)	[e](e) 2050 Health cost savings per person per year due to WWS ($/person/yr)	[f](f) 2050 Climate cost savings per person per year due to WWS ($/person/yr)	[g](g) 2050 Energy + health + climate cost savings due to WWS ($/person/yr)
Alabama	10.2	20.6	6.23	8,059	1,439	3,162	12,661
Alaska	8.4	16.7	5.38	18,221	715	5,155	24,091
Arizona	10.5	16.1	6.22	2,326	1,042	1,034	4,402
Arkansas	10.6	15.7	5.31	5,258	1,017	2,380	8,655
California	9.7	15.7	6.23	2,510	1,983	931	5,424
Colorado	10.4	20.1	5.29	6,360	888	1,917	9,164
Connecticut	10.0	20.0	7.28	3,586	1,453	1,158	6,197
Delaware	8.7	19.8	7.97	4,016	1,434	1,386	6,836
Florida	9.2	16.4	6.93	2,376	687	983	4,046
Georgia	10.2	18.2	7.08	4,316	1,250	1,660	7,226
Hawaii	11.1	39.1	7.13	7,291	963	1,491	9,745

Idaho	8.1	16.6	5.51	4,995	819	959	6,773
Illinois	11.3	14.7	5.04	4,004	1,724	2,008	7,737
Indiana	10.9	21.1	5.02	9,793	1,840	3,688	15,320
Iowa	11.1	16.1	4.69	9,061	1,343	3,548	13,952
Kansas	11.1	19.4	4.84	8,288	943	2,933	12,165
Kentucky	11.1	24.2	5.79	10,021	1,431	3,846	15,298
Louisiana	9.4	10.3	7.82	3,887	1,194	5,147	10,228
Maine	8.0	10.2	6.37	1,925	707	1,501	4,133
Maryland	11.1	23.1	7.82	4,370	1,414	1,168	6,951
Massachusetts	8.9	14.9	7.44	2,096	1,083	1,208	4,387
Michigan	10.9	20.1	6.24	4,966	1,199	1,798	7,963
Minnesota	10.8	19.4	5.42	6,805	807	1,717	9,329
Mississippi	9.3	16.1	6.19	5,250	1,314	2,484	9,048
Missouri	11.0	18.1	4.99	4,948	1,284	2,458	8,690
Montana	11.0	24.2	5.25	10,905	980	3,863	15,747
Nebraska	11.2	21.4	4.88	11,283	989	3,184	15,456
Nevada	8.6	14.5	6.80	2,281	974	1,020	4,275
New Hampshire	10.8	14.9	5.83	2,478	765	1,185	4,428
New Jersey	10.1	17.0	7.51	3,175	1,146	1,378	5,699
New Mexico	10.3	15.6	5.53	4,897	1,237	3,001	9,135
New York	9.8	14.9	6.90	2,117	1,301	1,155	4,573
North Carolina	10.6	17.3	7.61	3,162	1,005	1,351	5,517
North Dakota	11.1	18.6	4.88	16,618	686	9,312	26,616
Ohio	10.7	17.3	5.47	5,106	1,858	2,499	9,464
Oklahoma	9.5	13.6	4.91	5,188	1,138	3,161	9,487
Oregon	8.7	18.0	5.64	4,004	689	979	5,672
Pennsylvania	10.7	14.9	5.63	3,718	1,765	2,314	7,797
Rhode Island	8.0	11.0	7.79	829	1,061	1,117	3,007
South Carolina	11.1	21.9	7.52	6,084	1,353	1,912	9,349
South Dakota	10.7	16.2	4.77	8,346	747	2,209	11,301
Tennessee	11.2	22.9	5.82	7,162	1,374	1,726	10,262
Texas	9.6	14.1	5.73	6,035	931	2,303	9,269
Utah	10.6	21.1	5.65	6,015	1,261	2,116	9,393
Vermont	11.8	18.7	4.58	4,366	642	973	5,981
Virginia	10.4	19.0	7.45	4,089	1,011	1,292	6,392
Washington	10.0	19.1	5.25	5,139	715	1,027	6,882
West Virginia	11.1	21.7	5.37	9,011	1,400	6,670	17,080
Wisconsin	10.8	24.9	6.08	7,945	1,117	1,873	10,935
Wyoming	11.1	22.7	4.83	28,068	869	14,459	43,396
United States	10.13	16.97	6.12	4,501	1,259	1,798	7,557

a) Calculated as described in the text for U.S., averaged 2013 conventional fuel LCOE in Table 6, but for each state alone (including local transmission but excluding externality costs).

b) The 2030 LCOE cost for conventional fuels in each state was assumed to increase from the 2013 cost at the same rate as the increase in the state's electricity price from 2000-2012 (EIA, 2012a).

c) The 2030 LCOE of WWS in the state combines the 2050 distribution of WWS generators from Table 2 with the 2030 mean LCOEs for each WWS generator from Table 6.

d) Columns (c) minus (b) multiplied by the electric power generation in the state in 2050 from Table 1 (total energy consumption) and divided by the projected 2050 state population.

e) Total cost of air pollution per year in the state from Table 8 divided by the 2050 population of the state.

f) Total climate cost per year in the state from Table 9 divided by the 2050 population of the state.

g) The sum of columns (d), (e), and (f).

In summary, even 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.

8. Air Pollution and Global Warming Damage Costs Eliminated by WWS

Conversion to a 100% WWS energy infrastructure in the U.S. will eliminate energy-related air pollution mortality and morbidity and the associated health costs, and will eliminate energy-related climate change costs to the U.S. and the world. This section quantifies these benefits.

8.A. Air Pollution Cost Reductions due to WWS

To estimate air pollution mortality and its costs in each U.S. state, we use a top-down approach and a bottom-up approach.

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).

Table 8 shows the resulting medium estimates of premature mortality for each state in the U.S. due to $PM_{2.5}$ and O_3, as calculated with 2010-2012 air quality data. The medium values for the U.S. for $PM_{2.5}$ were ~48,000 premature mortalities/yr, with a range of 12,000-

95,000/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.

Table 8. Air pollution $PM_{2.5}$, O_3, total premature mortality (medium values), and costs of air pollution by state, 2010-2012 data.

State	Population (2012)	$PM_{2.5}$ Mortalities/yr	O_3 Mortalities/yr	Total Mortalities/yr	Cost ($billion/yr)
Alabama	4,822,023	754	200	954	7.8
Alaska	731,449	81	4	84	0.7
Arizona	6,553,255	986	531	1,518	12.4
Arkansas	2,949,131	397	51	448	3.7
California	38,041,430	10,011	2,516	12,528	102.7
Colorado	5,187,582	356	343	699	5.7
Connecticut	3,590,347	527	202	729	6.0
Delaware	917,092	154	44	198	1.6
Florida	19,317,568	2,115	566	2,681	22.0
Georgia	9,919,945	1,581	462	2,043	16.8
Hawaii	1,392,313	183	9	192	1.6
Idaho	1,595,728	152	68	219	1.8
Illinois	12,875,255	2,575	576	3,150	25.8
Indiana	6,537,334	1,341	363	1,704	14.0
Iowa	3,074,186	431	109	540	4.4
Kansas	2,885,905	275	102	377	3.1
Kentucky	4,380,415	663	223	887	7.3
Louisiana	4,601,893	625	155	780	6.4
Maine	1,329,192	99	37	136	1.1
Maryland	5,884,563	973	377	1,350	11.1
Massachusetts	6,646,144	765	268	1,033	8.5
Michigan	9,883,360	1,249	494	1,744	14.3
Minnesota	5,379,139	573	119	692	5.7
Mississippi	2,984,926	441	112	553	4.5
Missouri	6,021,988	816	308	1,123	9.2
Montana	1,005,141	132	7	139	1.1
Nebraska	1,855,525	198	47	245	2.0
Nevada	2,758,931	294	274	567	4.6
New Hampshire	1,320,718	129	42	171	1.4
New Jersey	8,864,590	1,208	320	1,528	12.5
New Mexico	2,085,538	242	111	353	2.9
New York	19,570,261	2,711	426	3,137	25.7
North Carolina	9,752,073	1,189	483	1,672	13.7
North Dakota	699,628	42	15	57	0.5
Ohio	11,544,225	2,234	686	2,920	23.9
Oklahoma	3,814,820	475	130	606	5.0
Oregon	3,899,353	391	63	453	3.7
Pennsylvania	12,763,536	2,494	571	3,065	25.1
Rhode Island	1,050,292	123	43	166	1.4
South Carolina	4,723,723	753	195	948	7.8
South Dakota	833,354	59	22	81	0.7
Tennessee	6,456,243	1,044	336	1,380	11.3
Texas	26,059,203	3,302	915	4,217	34.6
Utah	2,855,287	371	227	598	4.9

Vermont	626,011	47	15	62	0.5
Virginia	8,185,867	972	379	1,352	11.1
Washington	6,897,012	722	117	839	6.9
West Virginia	1,855,413	256	72	327	2.7
Wisconsin	5,726,398	705	229	934	7.7
Wyoming	576,412	34	28	62	0.5
United States	313,281,717	48,249	13,992	62,241	510.4

Premature mortality due to ozone exposure was estimated on the basis of the 8-hr maximum ozone each day over the period 2010-2012 (CARB, 2012). Relative risks and the ozone-health-risk equation were as in Jacobson (2010). The low ambient concentration threshold for ozone premature mortality was assumed to be 35 ppbv (Jacobson, 2010 and reference therein). Mortality due to $PM_{2.5}$ exposure was estimated on the basis of daily-averaged $PM_{2.5}$ over the period 2010-2012 (CARB, 2012) and the relative risks for long-term health impacts $PM_{2.5}$ (Pope et al., 2002) applied to all ages as in Lepeule et al. (2012) rather than those over 30 years old as in Pope et al. (2002). The threshold for $PM_{2.5}$ was zero but concentrations below 8 $\mu g/m^3$ were down-weighted as in Jacobson (2010). For each county in each state, mortality rates were averaged over the three-year period for each station to determine the station with the maximum average mortality rate. Daily air quality data from that station were then used with the 2012 county population and the relative risk in the health effects equation to determine the premature mortality in the county. For the $PM_{2.5}$ calculations, data were not available for 25% of the population and for the ozone calculations, data were not available for 26% of the population. For these populations, mortality rates were set equal to the minimum county value for a given state, as determined per the method specified above. In cases where 2012 data were unavailable, data from 2013 were used instead. $PM_{2.5}$ and ozone concentrations shown in the table above reflect the three-year average concentrations at the representative station(s) within each county. Since mortality rates were first calculated for each monitoring site in a county and then averaged over each station in the county, these average concentrations cannot directly be used to reproduce each county's mortality rate. In cases where "n/a" is shown, data within that county were not available (and the minimum county mortality rate within the state was used in these cases, as specified above).

Mortality and Nonmortality costs of air pollution. In general, the value of life is determined by economists based on what people are willing to pay to avoid health risks (Roman et al., 2012). USEPA (2006) and Levy et al. (2010) provided a central estimate for the statistical value of a human life at $7.7 million in 2007 dollars (based on 2000 GDP). Other costs due to air pollution include increased illness (morbidity from chronic bronchitis, heart disease, and asthma), hospitalizations, emergency-room visits, lost school days, lost work days, visibility degradation, agricultural and forest damage, materials damage, and ecological damage. USEPA (2011) estimates that these non-mortality-related costs comprise an additional ~7% of the mortality-related costs. These are broken down into morbidity (3.8%), recreational plus residential visibility loss (2.8%), agricultural plus forest productivity loss (0.45%), and materials plus ecological loss (residual) costs.

However, McCubbin and Delucchi's (1999) comprehensive analysis of air-pollution damages at every air quality monitor in the U.S found that the morbidity cost of air pollution (mainly chronic illness from exposure to particulate matter) might be as high as 25% to 30% of the mortality costs. Delucchi and McCubbin (2011) summarize studies that indicate that the cost of visibility and agriculture damages from motor-vehicle air pollution in the U.S. is at least 15% of the cost of health damages (including morbidity damages) from motor-vehicle air pollution. Thus, the total cost of air pollution, including morbidity and non-health damages, is at least ~$8.2 million/mortality, and probably over $10 million/mortality.

Given this information, the total social cost 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. If existing state policies to reduce future air pollution emissions do indeed result in pollution reductions, such policies would be additive to the first-step proposed polices to implement WWS in Section 14. However, while such policies may result in emission reductions per source, the number of sources is increasing, pollution is being emitted over larger areas as population spreads, international transport of air pollution is increasing, and a warmer climate is exacerbating remaining pollution, so it is not clear whether existing policies will indeed reduce future U.S. pollution mortalities notably.

8.B. Global-Warming Damage Costs Eliminated by 100% WWS in Each State

Energy-related greenhouse gas emissions from the U.S. cause climate-related damage to the world. In this section, we provide an estimate of these damages by state (Table 9), which a 100% WWS system in the U.S. would eliminate. 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.

Table 9. Percent of 2010 world CO_2 emissions by state and the U.S. as a whole (EIA, 2011) and avoided 2050 global warming cost by state due to converting to 100% WWS for all purposes.

State	Percent of world CO_2 emissions 2010	2050 avoided global warming cost ($bil/yr)
Alabama	0.40%	17.2
Alaska	0.12%	5.0
Arizona	0.29%	12.4
Arkansas	0.20%	8.6
California	1.12%	48.2
Colorado	0.29%	12.4
Connecticut	0.11%	4.8
Delaware	0.04%	1.6
Florida	0.73%	31.4
Georgia	0.52%	22.3
Hawaii	0.06%	2.4
Idaho	0.05%	2.1
Illinois	0.70%	30.1
Indiana	0.65%	28.0
Iowa	0.27%	11.7
Kansas	0.22%	9.6
Kentucky	0.45%	19.5
Louisiana	0.64%	27.6
Maine	0.05%	2.4

Maryland	0.21%	9.1
Massachusetts	0.22%	9.4
Michigan	0.50%	21.4
Minnesota	0.28%	12.1
Mississippi	0.20%	8.6
Missouri	0.41%	17.6
Montana	0.10%	4.5
Nebraska	0.15%	6.5
Nevada	0.11%	4.9
New Hampshire	0.05%	2.2
New Jersey	0.35%	15.1
New Mexico	0.16%	7.0
New York	0.53%	22.8
North Carolina	0.43%	18.4
North Dakota	0.15%	6.3
Ohio	0.75%	32.2
Oklahoma	0.32%	13.8
Oregon	0.12%	5.3
Pennsylvania	0.77%	32.9
Rhode Island	0.03%	1.4
South Carolina	0.26%	11.0
South Dakota	0.05%	2.0
Tennessee	0.33%	14.2
Texas	1.99%	85.6
Utah	0.19%	8.2
Vermont	0.02%	0.8
Virginia	0.33%	14.2
Washington	0.23%	9.9
West Virginia	0.30%	12.8
Wisconsin	0.30%	12.8
Wyoming	0.20%	8.4
United States	16.9%	728.6

Table 9 gives the percent of world CO_2 emissions by state as well as the percent of world emissions by the U.S. as a whole. (EIA, 2011). Since the global warming damage cost to the U.S. is caused by emissions from all states and countries worldwide, each state's contribution to U.S. damages is estimated by multiplying the cost of global warming to the U.S. by the fraction of total anthropogenic CO_2 emissions that are energy-related (~0.85) and each state's fraction of global CO_2 emissions (Table 9). When summed over the U.S., this results in damage costs to the U.S. alone (due to U.S. emissions) of $39 billion/yr in 2025 and $72.9 billion/yr in 2050.

U.S. emissions also cause global warming damage to the rest of the world. Anthoff et al. (2011) estimated the global climate-related damage cost of carbon worldwide to be at least an order of magnitude higher than the damage cost to the U.S. alone. This suggests that worldwide global warming damages from all U.S. energy-related emissions might be about $390 billion/yr in 2025 and ~$730 billion/yr in 2050.

The social cost of carbon (U.S. dollars per metric tonne of CO_2-eq. emitted, where CO_2-eq. is CO_2 plus other greenhouse gases when converted to the warming potential of CO_2) is intended to be an estimate of climate change damages, including changes in agricultural productivity, human health, and flood-related property damage, among others. However, it does not include all-important damages thus may be an underestimate (USEPA, 2014a). Nevertheless, its use is widespread. USEPA (2014a) estimates the social cost of carbon in 2011 dollars as follows: for the year 2025, \$50 (15-153)/tonne-CO_2-eq. and for 2050: \$76 (28-235)/tonne-CO_2-eq. The middle value is an average value at a 3% discount rate, whereas the low value is an average value at a 5% discount rate and the high value is the 95th percentile value at a 3% discount rate.

In 2012, U.S. greenhouse gas emissions were 6.526 billion metric tonnes CO_2-eq. (USEPA, 2014b) and represented ~17.5% of world emissions. According to the Intergovernmental Panel on Climate Change SRES A1B emission scenario, global annual CO_2 emissions may rise by 28.5% between 2012 and 2025 and by 57.5% between 2012 and 2050. Scaling these rates of increase to U.S. emissions gives 8.39 and 10.28 billion metric tonnes CO_2-eq. U.S. emissions in 2025 and 2050, respectively.

Multiplying the social cost of carbon by the U.S. emission rates and by the fraction of greenhouse gas emissions related to energy (~0.85) gives estimated global climate damages in 2025 and 2050 due to all U.S. anthropogenic CO_2-eq. emissions worldwide as \$360 (110-1100) billion/yr and \$660 (240-2050) billion/yr, respectively. These numbers are only slightly lower those from the first approach, likely due to the fact that the social cost of carbon may underestimate global warming costs (USEPA, 2014a).

Given this information, the total social cost due to air pollution mortality, morbidity, lost productivity, and visibility degradation in the U.S. 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 represents a savings equivalent to ~3.15 (0.98-7.13) of the U.S. 2012 gross domestic product.

In sum, converting the U.S. to WWS would avoid \$510 (158-1,155) billion/year in air pollution 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 2), 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.

9. Impacts of WWS on Jobs and Earnings in the Electric Power Sector.

This section provides estimates of the jobs and total earnings created by implementing WWS-based electricity and the jobs and earnings lost in the displaced fossil-fuel electricity and petroleum industries. The analysis does not include the potential job and revenue gains in other affected industries such as the manufacturing of electric vehicles, fuel cells or electricity storage.

9.A. JEDI Job Creation Analysis

Changes in jobs and total earnings are estimated here first with the Jobs and Economic Development Impact (JEDI) models (NREL, 2013). These are economic input-output models programmed by default for local and state levels. They incorporate three levels of impacts: 1) project development and onsite labor impacts; 2) local revenue and supply chain impacts; and 3) induced impacts. Jobs and revenue are reported for two phases of development: 1) the construction period and 2) operating years.

Scenarios for wind and solar powered electricity generation were run assuming that the WWS electricity sector is fully developed by 2050. Existing capacities were excluded from the calculations. As construction period jobs are temporary in nature, JEDI models report job creation in this stage as full-time equivalents (FTE, equal to 2,080 hours of work per year). We assume for this calculation that each year from 2010 to 2050 1/40th of the WWS infrastructure is built. All earnings are reported in 2010 real U.S. dollar values.

Table 10. 40-year construction jobs, 40-year operation jobs produced, construction plus operation jobs produced minus jobs lost, annual earnings corresponding to construction and operation jobs, and net earnings from contruction plus operation jobs created minus jobs lost; by state due to converting to WWS.

State	40-year construction jobs	40-year operation jobs	Job losses in current energy industry	40-year construction plus operation jobs created minus jobs lost	Earnings from new 40-year construction jobs ($bil/yr)	Earnings from new 40-year operation jobs ($bil/yr)	Net earnings from construction plus operation jobs created minus jobs lost ($bil/yr)
Alabama	130,384	49,564	57,095	122,853	7.00	2.96	6.53
Alaska	17,253	17,961	24,423	10,791	0.98	1.24	0.75
Arizona	89,743	32,645	85,425	36,963	5.23	2.04	2.15
Arkansas	57,144	22,781	38,570	41,356	3.13	1.47	2.28
California	442,159	190,557	413,097	219,619	24.59	12.02	11.83
Colorado	64,304	26,563	76,576	14,291	3.68	1.74	0.83
Connecticut	44,791	23,964	34,194	34,561	2.38	1.48	1.80
Delaware	10,431	7,899	8,922	9,408	0.57	0.50	0.53
Florida	375,480	145,386	173,635	347,232	20.16	8.77	18.52
Georgia	191,598	93,250	95,086	189,762	10.32	5.72	10.33
Hawaii	10,149	4,997	13,599	1,547	0.55	0.32	0.06
Idaho	24,329	9,267	14,746	18,850	1.35	0.60	1.07
Illinois	164,664	71,526	138,722	97,468	8.87	4.69	5.24
Indiana	152,897	59,994	71,464	141,427	8.10	3.85	7.66
Iowa	57,789	24,160	29,899	52,050	3.11	1.59	2.91
Kansas	35,645	15,981	42,836	8,789	2.04	1.07	0.54
Kentucky	147,803	49,601	62,687	134,718	7.75	2.92	6.90
Louisiana	177,605	144,283	134,860	187,028	9.97	9.11	10.99
Maine	17,913	12,872	12,446	18,340	0.97	0.84	1.06
Maryland	66,461	44,579	54,286	56,754	3.60	2.81	3.15
Massachusetts	61,376	42,832	64,380	39,829	3.33	2.74	2.20
Michigan	108,680	69,523	99,191	79,012	5.96	4.58	4.59

Minnesota	60,779	36,740	56,345	41,174	3.37	2.49	2.47
Mississippi	98,152	39,818	39,126	98,844	5.17	2.39	5.21
Missouri	76,096	28,634	59,914	44,816	4.11	1.84	2.35
Montana	16,018	6,418	16,202	6,234	0.90	0.41	0.34
Nebraska	29,028	12,819	23,343	18,503	1.64	0.85	1.09
Nevada	51,187	16,559	27,589	40,157	2.82	1.03	2.19
New Hampshire	15,519	8,113	13,662	9,970	0.83	0.52	0.53
New Jersey	104,608	70,851	90,836	84,623	5.65	4.48	4.68
New Mexico	24,572	10,835	41,674	-6,267	1.42	0.73	-0.35
New York	180,240	97,023	187,203	90,060	9.58	6.04	4.39
North Carolina	143,965	85,792	94,223	135,534	7.89	5.36	7.60
North Dakota	21,666	8,502	26,690	3,479	1.17	0.54	0.10
Ohio	176,161	75,010	123,109	128,062	9.41	4.78	6.80
Oklahoma	52,345	22,186	95,445	-20,914	2.95	1.46	-1.31
Oregon	36,958	20,329	36,020	21,267	2.05	1.32	1.20
Pennsylvania	286,658	110,478	158,788	238,349	14.88	6.67	12.02
Rhode Island	8,791	6,633	9,892	5,531	0.48	0.42	0.31
South Carolina	68,089	45,941	48,132	65,899	3.78	2.89	3.78
South Dakota	11,351	5,051	8,028	8,374	0.65	0.33	0.51
Tennessee	175,514	59,238	63,345	171,407	9.26	3.49	8.95
Texas	505,803	284,098	571,429	218,472	29.61	18.76	14.09
Utah	43,961	17,018	37,942	23,037	2.47	1.09	1.28
Vermont	5,603	2,014	6,455	1,162	0.29	0.13	0.03
Virginia	115,676	72,296	83,707	104,264	6.38	4.55	5.91
Washington	71,249	38,205	67,603	41,851	3.79	2.47	2.20
West Virginia	47,550	17,701	53,862	11,389	2.49	1.08	0.33
Wisconsin	63,871	39,460	54,168	49,163	3.51	2.60	2.86
Wyoming	15,521	7,397	40,009	-17,091	0.89	0.50	-1.02
United States	4,955,528	2,405,343	3,880,875	3,479,995	271	152	190

40-year jobs are number of full-time equivalent (FTE) 1-year (2080 hours of work per year) jobs for 40 years. Earnings are in the form of wages, services, and supply-chain impacts. During the construction period, they are the earnings during all construction. For the operation period, they are the annual earnings.

The JEDI models are economic input-output models that have several uncertainties (e.g. Linowes, 2012). To evaluate the robustness of the models, we compared results with calculations derived from an aggregation of 15 different renewable energy job creation models (Wei et al., 2010). These included input/output models such as JEDI, and bottom-up analytical models. Table 10 suggests that the JEDI models estimated the number of 40-year operation jobs as 2.4 million across the U.S. due to WWS. This estimate falls within the range of 1.1-6 million jobs derived from the aggregation of models shown in Table 11.

Table 11. Estimated number of permanent operations, maintenance, and fuel processing jobs per installed MW of energy source. Installed MW are of proposed new plants.

Energy Technology	Installed MW	Jobs per installed MW	Number of permanent jobs
Onshore wind	1,757,737	0.14-0.4	246,000-703,000
Offshore wind	904,726	0.14-0.4	127,000-362,000
Wave device	33,657	0.14-0.4	4,700-13,000
Geothermal plant	26,529	1.67-1.78	44,000-47,000
Hydroelectric plant	4,926	1.14	5,600
Tidal turbine	10,687	0.14-0.4	1,500-4,300
Residential roof PV	637,866	0.12-1	77,000-638,000

Com/gov roof PV	493,818	0.12-1	59,000-494,000
Solar PV plant	2,922,206	0.12-1	351,000-2,920,000
CSP plant	833,012	0.22-1	183,000-833,000
Total	7,625,164		1,100,000-6,000,000

9.B. Job Loss Analysis

Table 12 provides estimates of the number of U.S. jobs that may be lost in the oil, gas, and uranium extraction and production industries; petroleum refining industry; coal, gas, and nuclear power plant operation industries; fuel transportation industry, and other fuel-related industries upon a shift to WWS.

Table 12. U.S. job loss upon eliminating energy generation and use from the fossil fuel and nuclear sectors.

Energy Sector	Number of Jobs Lost
Oil and gas extraction/production	806,300[a]
Petroleum refining	73,900[b]
Coal/gas power plant operation	259,400[c]
Coal mining	89,700[d]
Uranium extraction/production	1,160[e]
Nuclear power plant operation	80,500[f]
Coal and oil transportation	2,448,300[g]
Other	171,500[h]
Less petroleum jobs retained	-50,000[i]
Total	**3,881,000**

[a] EMSI (2012).

[b] Workers employed in U.S. refineries from EIA (2014a). State values are estimated by multiplying the U.S. total by the fraction of U.S. barrels of crude oil distilled in each state from EIA (2014b).

[c] Includes coal plant operators, gas plant operators, compressor and gas pumping station operators, pump system operators, refinery operators, stationary engineers and boiler operators, and service unit operators for oil, gas, and mining. Coal data from Sourcewatch (2014). All other data from ONET online (2014).

[d] EIA (2014c)

[e] Multiply U.S. uranium mining employment across 12 U.S. states that mine uranium from EIA (2014d). State values are estimated by multiplying the total by the state population divided by the total population of the 12 states.

[f] NEI (2014).

[g] Multiply the total number of direct U.S. jobs in transportation (11,000,000) from USDOT (2014) by the ratio (0.287 in 2007) of weight of oil and coal shipped in the U.S. relative to the total weight of commodities shipped from USDOT (2012) and by the fraction of transportation jobs that are relevant to oil and coal transportation (0.78) from USBLS (2014) and by the fraction of the U.S. population in each state.

[h] Other includes accountants, auditors, administrative assistants, chemical engineers, geoscientists, industrial engineers, mechanical engineers, petroleum attorneys, petroleum engineers, and service station attendants associated with oil and gas, Petrostrategies, Inc. (2014).

[i] See text for discussion of jobs retained.

Although the petroleum industry will lose jobs upon the elimination of extraction of crude oil in the U.S., jobs in the production of non-fuel petroleum commodities such as lubricants, asphalt, petrochemical feedstocks, and petroleum coke will remain. The number of these jobs is estimated as follows: currently, 195,000 people work in oil and gas production alone across the U.S. (USBLS, 2012). Assuming 50% of these workers are in oil production, 97,500 jobs exist in the U.S. oil production industry. Petroleum refineries employ another 73,900 workers (Table 12). Nationally, the non-fuel output from oil refineries is ~10% of refinery output (EIA, 2013b). We thus assume that only 10% (~17,000) of petroleum production and refining jobs will remain upon conversion to WWS. We assume another 33,000 jobs will remain for transporting this petroleum for a total of 50,000 jobs remaining. These jobs are assigned to states with current oil refining based on the current capacity of refining.

In sum, the shift to WWS may result in the displacement of ~3.88 million jobs in current fossil- and nuclear-related industries in the U.S. At $60,000/yr per job – close to the average for the WWS jobs – the corresponding loss in revenues is ~$233 billion.

9.C. Jobs analysis summary

The JEDI models 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.

10. Reducing Energy Use in Buildings, Neighborhoods, and Commercial Complexes

The proposed state plans will continue and enhance existing efforts to improve energy efficiency in residential, commercial, institutional, and government buildings, thereby reducing energy demand in each state. Current state energy policies promote building efficiency through appliance standards, regulations, tax incentives, education, and renewable energy portfolios.

A number of studies have estimated that efficiency measures can reduce energy use in non-transportation sectors by 20 to 30% or more (McKinsey and Co., 2009; Siddiqui, 2009; Farese, 2012; Kavalec et al., 2012; CEC, 2012). Thus, the assumption in Table 1 of a ~5.5% demand reduction due to end-use energy efficiency measures (in addition to ~32% additional demand reductions due to the conversion to electricity and elimination of mining and processing of fuels) upon complete conversion to WWS is conservative. If the achieved demand reduction is larger than ~5.5%, then meeting each state’s energy needs with 100% WWS will be easier to implement.

Several technologies can further improve energy efficiency (e.g., Navigant Consulting, 2012). These include

- LED lighting (residential, commercial and street/parking applications)
- Optimized hot/dry climate air conditioning systems
- Evaporative cooling
- Indirect evaporative cooling
- Ductless air conditioning
- Water-cooled heat exchangers for HVAC equipment
- Residential night ventilation cooling
- Heat pump water heaters
- Condensing gas water heaters
- Improved data center design
- Improved air-flow management
- Variable-speed computer room air conditioning (CRAC) compressors
- Advanced lighting controls
- Evaporator fan controller for medium temperature walk-in evaporator systems
- Combined space and water heater
- Advanced HID lighting – pulse start and ceramic metal halide
- Fault detection and diagnostics
- Variable refrigerant flow
- Advanced steam trap systems
- Reduced working temperature for asphalt
- High performance rooftop unit
- Comprehensive commercial HVAC rooftop unit quality maintenance

These energy efficiency measures are viewed as Demand Side Management (DSM) techniques by electric utilities. DSM measures have the ability to reduce both energy consumption (MWh) and peak load (MW). When DSM tools are used along with tradition power planning measures they result in Integrated Resource Planning (IRP). DSM measures reduce environmental impacts of energy consumption while avoiding costs and risk of building new supply. An additional benefit to utilities of DSM measures is to defer new capitally intensive projects to meet electric growth as well as reduce consumer energy costs.

An additional benefit of DMS measures is compounded energy savings. Due to losses along the electric grid, reducing end-use consumption reduces incremental distribution, transmission, and plant losses. Another benefit is that DSM reduces the need for additional air conditioning required to cool buildings that heat up due to the conversion of electricity to heat in buildings, since it reduces electricity use in buildings.

DSM measures are often the best option for reducing electricity growth and providing high value electricity savings at a lower cost. The use of DSM measures is one of the few current sustainable energy options with a negative Marginal Abatement Cost ($\$/MTCO_2$), meaning that they both save money and reduce emissions. Large-scale implementation of DSM has been widely successful with one of the best-known measures being the U.S. refrigerator standards. Since 1975 refrigerators have increased in volume by an average of 11% while reducing electricity consumption by almost 80% (from 1,800 to 400 kWh/yr) and at lower cost. Through the use of proper incentives, tax credits, mandates, and further developing information of DSM measures energy, efficiency has the ability to reduce greatly energy consumption in a cost-effective way.

11. State Tax Revenue Consideration

The implementation of this plan will affect state tax revenues and require tax policy changes to ensure that revenues remain constant in each state. As a large sector of the U.S. is employed or involved indirectly with the production, transport, and use of fossil fuels, a substantial transition in the source of governmental tax revenue will be needed. Such a transition should not decrease net revenue since new jobs and taxable income and other taxable income streams will increase.

Revenues directly associated with the sale of petroleum fuels, such as gasoline and diesel fuel taxes, will diminish as the vehicle fleet transitions to BEVs and HFCVs altogether. One way to offset motor fuel revenue losses is to impose a vehicle registration renewal fee on vehicles that don't use motor fuel. Other tax revenues associated with passenger vehicle use, such as motor vehicle fees, taxi surcharge fees, and auto rental taxes, are not expected to decrease significantly upon a conversion to BEVs and HFCVs.

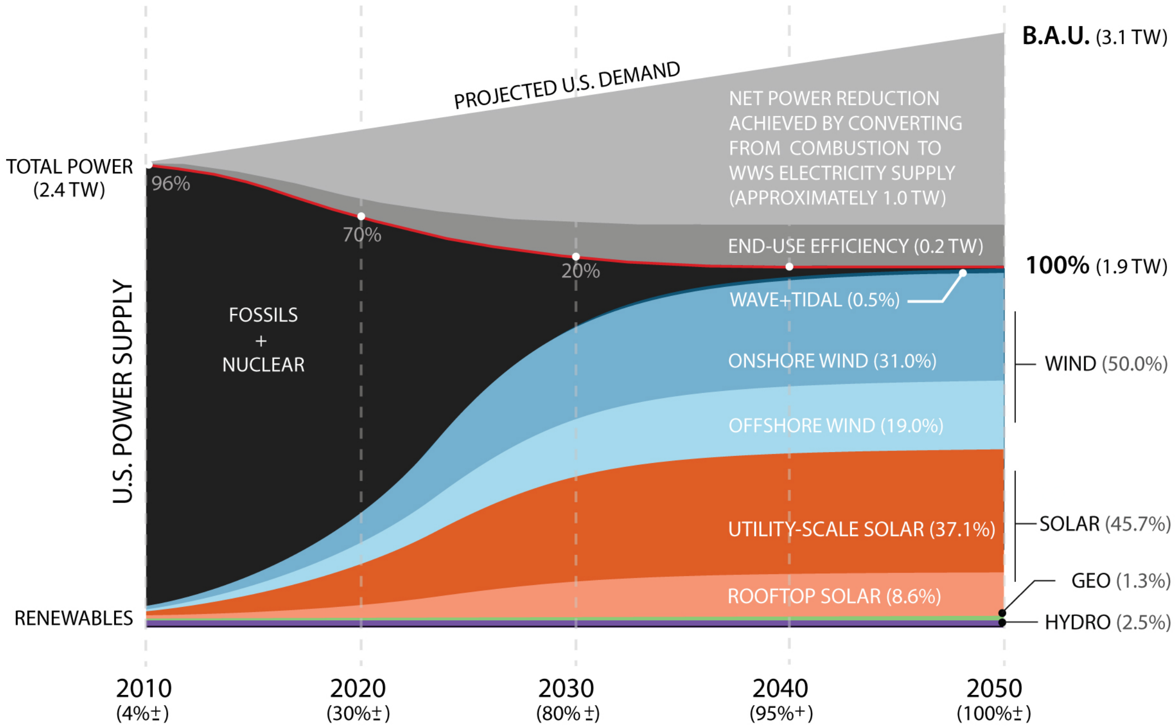
As more state infrastructure is electrified, revenues from utility taxes will increase. Property taxes, other sales and use taxes, corporation taxes, private rail car taxes, energy resource surcharges, quarterly public utility commission fees, and penalties on public utility commission fees are unlikely to change much. Environmental and hazardous waste fees and oil and gas lease revenues will likely decrease, but these revenues are small.

The largest change that will occur is the end of export of money for the international importation of oil into the U.S. A net of $330 billion, or ~$1000/person is spent each year on importing oil. This exported money will now remain in the U.S. economy creating compounding cash flows, increasing tax revenue.

12. Timeline of Implementation of the Roadmaps

Figure 5 shows an average timeline for the implementation of the roadmaps presented here. The plans calls for all new electric power generators installed by 2020 to be WWS generators and existing conventional generators to be phased out gradually, such that by 2030, 80-85% of the existing infrastructure is converted and by 2050, 100% is converted. Similarly, all new heating and cooling technologies are proposed to be WWS technologies by 2020 and existing technologies, replaced over time, but by no later than 2050.

Figure 5. Change in U.S. end-use power demand for all purposes (electricity, transportation, heating/cooling, and industry) among conventional fuels and WWS energy over time based on the sum of demand among all state roadmaps proposed here. Total power demand decreases upon conversion to WWS due to the efficiency of electricity over combustion and end-use energy efficiency measures. The percentages above the fossils plus nuclear curve are of remaining penetration of those energy sources each decade. The percentages next to each WWS source are the final estimated penetration of the source. The 100% demarcation in 2050 indicates that 100% of all-purpose power is provided by WWS technologies by 2050, and the power demand by that time has decreased. Karl Burkart, personal communication.



For transportation, the transition to BEVs and HFCVs is expected to occur more rapidly than in the power generation sector due to the rapid turnover time of the vehicle fleet (~15 years) and the efficiency of BEVs and HFCVs over fossil-fuel combustion vehicles. BEVs and HFCVs exist today, but are anticipated to be the only new vehicles sold by 2020. Freight and passenger rail, freight trucks, tractors, construction machines, ships, and aircraft also will be converted to 100% WWS with a combination of battery-electric and hybrid battery-electric/hydrogen-fuel-cell or, in the case of aircraft, batter-electric/cryogenic-hydrogen energy systems. The vehicle charging and hydrogen fueling infrastructures will need to be developed. With hydrogen fueling, on-site electrolysis using transmitted electricity to produce hydrogen may be more efficient than producing hydrogen remotely and piping it to fueling stations. Some conversion in transportation can be obviated by better transportation planning, including an increased emphasis on transit, biking, and walking. Policy measures to jump start these processes are discussed shortly.

13. Current Status of Conversion to WWS

The U.S. has already made strides toward converting to WWS. For example, at the end of 2013, approximately 4.4% of all U.S. electric power produced was from wind, 0.21% was from solar, 0.42% was from geothermal, and 6.8% was from hydroelectric power (EIA, 2014e), for a total of 11.83% from WWS resources. The growth in wind and solar, in particularly, has been rapid relative to just 2-3 years prior. Because the “fuel” cost of WWS electric power is zero, costs of these electricity sources will stay flat over time, whereas fossil-fuel costs will continue to rise, as they have in the past, causing a natural transition to WWS electric power generation. Although the capital cost of WWS electric power sources is often higher than that of fossil fuel sources, the zero fuel cost stabilizes prices of WWS generators, resulting in lower long-term costs of WWS generators compared with fossil fuel generators. This factor suggests further that WWS technologies will ultimately replace conventional fuels on their own, although policies are needed to speed up the transition to obtain complete replacement by 2050.

With regard to transportation, as of December 2013, the U.S. had 170,000 plug-in electric vehicles on the road (0.067% of the U.S. vehicle fleet of 253 million vehicles), with 57% of these purchased during 2013. The 2013 growth rate represented an 84% increase over 2012. Further, at the end of 2013, there were 19,500 public charging outlets in the U.S., including 378 DC chargers (Wikipedia, 2014). Due to the efficiency and thus the low "fuel" cost of an electric vehicle versus a gasoline vehicle (e.g., $0.80/gallon equivalent for electric versus $4/gallon for gasoline), a typical person driving 15,000 miles/year for 15 years will save ~$20,000 in fuel costs with an electric vehicle. In addition, fast DC superchargers allow 300-miles of charging in one hour. The low fuel cost, greater safety (less rollover, greater crush buffer in the front, and cannot explode), greater acceleration, and low maintenance costs (because they have fewer moving parts) of electric vehicles suggest that vehicle electrification will increase naturally over the coming decades.

With regard to heating, 33.5% of 113.6 million U.S. homes are already heated with electric heating (either central electric heated forced air, heat pumps, portable electric heaters, and other electric equipment exhaust) (EIA, 2014f). Energy efficiency measures are also being implemented nationally. For example, the California Public Utilities Commission and California Energy Commission have set the goal that all new homes in California will produce as much energy as they consume by 2020 (net zero energy).

14. Recommended First Steps

While U.S. states have already enacted some legislation to reduce greenhouse gas and air pollutant emissions and convert to renewable energy, greater changes are needed to reach 100% WWS by 2050. Here, some short-term policy options are listed to help with this goal at the state level.

14.1 State Planning and Incentive Structures

- Create a green building tax credit program for the corporate sector.
- Create energy performance rating systems with minimum performance requirements to assess energy efficiency levels across the state and pinpoint areas for improvement.
- Lock in the remaining in-state coal-fired power plants to retire under enforceable commitments. At the same time, streamline the permit approval process for WWS power generators and high-capacity transmission lines.

- Within existing regional planning efforts, work with local and regional governments to manage zoning and permitting issues or pre-approve sites to reduce the costs and uncertainty of projects and expedite their physical build-out. In the case of offshore wind, include the federal government in planning and management efforts.

14.2. Energy Efficiency Actions

- Expand Renewable Energy Standards and Energy Efficiency Resource Standards.

- Introduce a Public Benefit Funds (PBF) program for energy efficiency. The program is funded with a non-bypassable charge on consumers' electricity bills for distribution services. These funds generate capital that sponsor energy efficiency programs, and research and development related to clean energy technologies and training.

- Promote, though municipal financing, incentives, and rebates, energy efficiency measures in buildings. Efficiency measures include, but are not limited to, using LED lighting; optimized air conditioning systems; evaporative cooling; ductless air conditioning; water-cooled heat exchangers; night ventilation cooling; heat-pump water heaters; improved data center design; improved air flow management; advanced lighting controls; combined space and water heaters; variable refrigerant flow; and improved wall, floor, ceiling, and pipe insulation (e.g., Navigant Consulting, 2012). Other measures include sealing leaks in windows, doors, and fireplaces, converting to double-paned windows, using more passive solar heating, monitoring building energy use to determine wasteful processes, and performing an energy audit to discover energy waste.

- Continuously revise building codes for construction of new buildings and renovation of existing buildings as new technologies become readily available.

- Incentivize landlords' investment in efficiency. Allow owners of multi-family buildings to take a property tax exemption for energy efficiency improvements made in their buildings that provide benefits to their tenants.

- Create a rebate program that targets energy efficiency in appliances and processes. Efficiency measures include, but are not limited to, upgrading appliances to those that use less electricity, using hot water circulation pumps on a timer, converting to LED light bulbs, etc.

- Encourage conversion from natural gas water and air heaters to heat pumps (air and ground-source) and rooftop solar thermal hot water pre-heaters. Incentivize more use of efficient lighting in buildings and on city streets. Publicize ground source heat pumps as a key energy efficiency technology for Washington by retrofitting a high-profile state building.

14.3. Energy Supply Action

Energy Supply Action includes the actions taken that result in the use of cleaner energy sources. Renewable portfolio standards, interconnection standards, and public benefit funds for clean energy supply all fall under this category.

- Increase Renewable Portfolio Standards (RPS).

- Extend or create state solar production tax credits.

- Encourage the progression toward WWS by implementing a tax on emissions by current utilities.

- Streamline the small-scale solar and wind installation permitting process. Create common codes, fee structures, and filing procedures across the state.

- Encourage clean-energy backup emergency power systems rather than diesel/gasoline generators at both the household and community levels. Work with industry to implement home or community energy storage (through battery systems, including re-purposed BEV batteries) accompanying rooftop solar to mitigate problems associated with grid power losses.

14.4. Utility Planning and Incentive Structures

- Implement virtual net metering (VNM) for small-scale energy systems. Virtual net metering allows a utility customer to assign the net production from an electrical generator on his or her property (e.g., solar PV) to another metered account that is not physically connected to that generator. This allows credits from a single solar PV system to be distributed among multiple electric service accounts, such as in low-income residential housing complexes, apartment complexes, school districts, multi-store shopping centers, or a residential neighborhood with multiple residents and one PV system. To that end,
    1. Remove the necessity for subscribers to have proprietorship in the energy-generating site.
    2. Expand or eliminate the capacity limit of net-metering for each utility.
    3. Remove the barrier to inter-load zone transmission of net-metered renewable power.

- Develop peak-load management strategies to account for the variability of renewable energy integration to the grid as California did recently by setting a goal to install 1.3 GWh of grid storage by 2020.

- Encourage utilities to use demand-response grid management to reduce the need for short-term energy backup on the grid.

14.5. Transportation

- Create a governor-appointed EV Advisory Council, as has been done in Illinois and Connecticut, to recommend strategies for EV infrastructure and policies.

- Leverage and augment the technical and financial assistance of the U. S. Department of Energy's "Clean Cities Program" activities, focusing on the deployment of BEVs.

- Adopt legislation mandating the transition to plug-in electric vehicles for short- and medium distance government transportation and encouraging the transition for commercial and personal vehicles through purchase incentives and rebates.

- Use incentives or mandates to stimulate the growth of fleets of electric and/or hydrogen fuel cell/electric hybrid buses starting with a few and gradually growing the fleets. Electric or hydrogen fuel cell ferries, riverboats, and other local shipping should be encouraged as well.

- Encourage and ease the permitting process for the installation of electric charging stations in public parking lots, hotels, suburban metro stations, on streets, and in residential and commercial garages.

- Set up time-of-use electricity rates to encourage charging at night.

- Use excess wind and solar produced by WWS electric power generators to produce hydrogen (by electrolysis) for transportation and industry and to provide district heat for water and air (as done in Denmark) instead of curtailing the wind and solar.

- Encourage the electrification of freight rail and shift freight from trucks to rail.

- Encourage more use of public transit by increasing availability and providing incentives. Successful programs have been seen on college or university campuses in which commuters receive compensation for not purchasing a parking pass and opting to use public transportation or personal bicycles for their commute.

- Increase safe biking and walking infrastructure, such as dedicated bike lanes, sidewalks, crosswalks, timed walk signals, etc.

14.6. Industrial Processes

- Provide tax or other financial incentives for industry to convert to electricity and electrolytic hydrogen for high temperature and manufacturing processes where they are not currently used.

- Provide tax or other financial incentives to encourage industries to use WWS electric power generation for on-site electric power (private) generation.

15. Summary

This study proposed that converting the U.S. energy infrastructure for all purposes into a clean and sustainable one powered by wind, water, and sunlight (WWS) producing electricity and hydrogen is technically and economically feasible. It evaluated U.S. WWS resources and proposed a mix of WWS generators that could match projected 2050 demand. It also evaluated the land and water areas required, potential of the generators to match demand (relying on previous optimization model results), direct, air pollution, and climate cost changes, and net jobs created from such a conversion.

The timeline for conversion was proposed as follows: all new installations would be WWS by 2020, and existing infrastructure would gradually be replaced, with about 80-85% replaced by 2030 and 100% by 2050.

The conversion from combustion to a completely electrified system for all purposes is calculated to reduce U.S.-averaged end-use power demand ~37.6% with ~85% of this due to electrification and 15% due to end-use energy efficiency improvements. Additional end-use energy efficiency measures should reduce power demand further. The conversion to WWS should stabilize energy prices since fuel costs will be zero.

Remaining all-purpose end-use U.S. power demand is proposed to be met (based on 2050 energy estimates) with 351,500 onshore 5-MW wind turbines (providing 31.0% of U.S. energy for all purposes), 181,000 off-shore 5-MW wind turbines (19.0%), 58,500 50-MW utility-scale solar-PV power plants (29.6%), 8,330 100-MW utility-scale CSP power plants (7.54%), 128 million 5-kW residential rooftop PV systems (4.7%), 4.9 million 100-kW commercial/government rooftop systems (3.9%), 265 100-MW geothermal plants (1.3%), 45,000 0.75-MW wave devices (0.37%), 10,700 1-MW tidal turbines (0.13%), and virtually no new hydroelectric power plants, but the capacity of existing plants would be increased so that hydro supplies 2.46% of all-purpose power. This is just one plausible mix. Least-cost energy-system optimization studies and practical implementation considerations will determine the actual design and operation of the energy system and may result in technology mixes different than proposed here (e.g., more power plant PV, less rooftop PV).

Several methods exist 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 in remaining gaps; (B) using demand-response grid management to shift times of demand to match better with the timing of WWS power supply; (C) 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 water and air 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 such as molten nitrate salt and soil, batteries, or other storage media; and (F) storing energy in electric-vehicle batteries for later extraction (vehicle-to-grid).

The additional footprint on land for WWS devices is equivalent to about 0.44% of the U.S. land area, mostly for utility scale PV. This does not account for land gained from eliminating the current energy infrastructure. An additional on-land spacing area of about

1.7% is required for onshore wind, but this area can be used for multiple purposes, such as open space, agricultural land, or grazing land. The land footprint and spacing areas (open space between devices) in the proposed scenario can be reduced by shifting more land based WWS generators to the ocean, lakes, and rooftops.

2030 electricity costs are estimated to be 6.1 (5.2-7.1) U.S. ¢/kWh (including local transmission and distribution costs) in the U.S. average for the combination of WWS technologies proposed, which compares with about 22.7 (22.0-23.3) ¢/kWh for fossil-fuel generators in 2030, of which 5.7 ¢/kWh is externality cost. When long-distance transmission is built, it is estimated to cost an additional 1 (0.3-3) ¢/kWh for 1200-2000 km high-voltage direct current lines.

The 50-state roadmaps are anticipated to create ~5 million 40-year construction jobs and ~2.4 million 40-year operation jobs for the energy facilities alone, outweighing the ~3.9 million jobs lost to give a net gain of 3.48 million 40-year jobs. Earnings during the 40-year construction period for these facilities (in the form of wages, local revenue, and local supply-chain impacts) are estimated to be ~$270 billion/yr in 2010 dollars and annual earnings during operation of the WWS facilities are estimated at ~$150 billion/year. Net earnings from construction plus operation minus lost earnings from lost jobs are estimated at ~$190 billion/yr.

The state roadmaps will reduce U.S. air pollution mortality by ~62,000 (19,000-116,000) premature mortalities/yr, and its costs by $510 (158-1,155) billion/yr in health costs, or 3.15 (0.98-7.13) of the 2012 U.S. GDP. The U.S. emission decreases will reduce 2050 worldwide global-warming costs due to U.S. emissions by at least $730 billion/yr.

The savings in health cost to the U.S. plus climate cost to the world due to U.S. emissions may equal the capital and installation cost of WWS generators within 11.0 (7.3-15.4) years.

The roadmaps will increase revenues from current utility taxes, due to the increased use of electricity. At the same time, they will reduce fuel-tax revenues. Either utility taxes or mileage-base road fees can compensate for fuel-tax losses.

The implementation of plans such as these in countries worldwide will essentially eliminate energy-related global warming; air, soil, and water pollution; and energy insecurity.

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