Energy & Environmental Science

Accepted Manuscript

ROYAL SOCIETY OF CHEMISTRY

www.rsc.org/ees

100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for the 50 United States

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Energy and Environmental Sciences
May 20, 2015

Abstract

This study presents roadmaps for each of the 50 United States to convert their all-purpose energy systems (for electricity, transportation, heating/cooling, and industry) to ones powered entirely by wind, water, and sunlight (WWS). The plans contemplate 80-85% of existing energy replaced by 2030 and 100% replaced by 2050. Conversion would reduce each state's end-use power demand by a mean of ~39.3% with ~82.4% of this due to the efficiency of electrification and the rest due to end-use energy efficiency improvements. Year 2050 end-use U.S. all-purpose load would be met with ~30.9% onshore wind, ~19.1% offshore wind, ~30.7% utility-scale photovoltaics (PV), ~7.2% rooftop PV, ~7.3% concentrated solar power (CSP) with storage, ~1.25% geothermal power, ~0.37% wave power, ~0.14% tidal power, and ~3.01% hydroelectric power. Based on a parallel grid integration study, an additional 4.4% and 7.2% of power beyond that needed for annual loads would be supplied by CSP with storage and solar thermal for heat, respectively, for peaking and grid stability. Over all 50 states, converting would provide ~3.9 million 40-year construction jobs and ~2.0 million 40-year operation jobs for the energy facilities alone, the sum of which would outweigh the ~3.9 million jobs lost in the conventional energy sector. Converting would also eliminate ~62,000 (19,000-115,000) U.S. air pollution premature mortalities/yr today and ~46,000 (12,000-104,000) in 2050, avoiding ~$600 ($85-$2,400) bil./yr (2013 dollars) in 2050, equivalent to ~3.6 (0.5-14.3) percent of the 2014 U.S. gross domestic product. Converting would further eliminate ~$3.3 (1.9-7.1) tril./yr in 2050 global warming costs to the world due to U.S. emissions. These plans will result in each person in the U.S. in 2050 saving ~$260 (190-320)/yr in energy costs ($2013 dollars) and U.S. health and global climate costs per person decreasing by ~$1,500 (210-6,000)/yr and ~$8,300 (4,700-17,600)/yr, respectively. The new footprint over land required will be ~0.42% of U.S. land. The spacing area between wind turbines, which can be used for multiple purposes, will be ~1.6% of U.S. land. Thus, 100% conversions are technically and economically feasible with little downside. These roadmaps may therefore reduce social and political barriers to implementing clean-energy policies.

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

1. Introduction

This paper presents a consistent set of roadmaps to convert each of the 50 U.S. states' all-purpose (electricity, transportation, heating/cooling, and industry) energy infrastructures to ones powered 100% 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 job creation. However, in most if not all states these goals are limited to partial emission reductions by 2050 (see, for example, Morrison et al., 2015 for a review of California roadmaps), and no set of consistently-developed roadmaps exist for every U.S. state. By contrast, the roadmaps here provide a consistent set of pathways to eliminate 100% of present-day greenhouse gas and air pollutant emissions from energy by 2050 in all 50 sates while growing the number of jobs and stabilizing energy prices. A separate study (Jacobson et al., 2015) provides a grid integration analysis to examine the ability of the intermittent energy produced from the state plans here, in combination, to match time-varying electric and thermal loads when combined with storage and demand response.

The methods used here to create each state roadmap are broadly similar to those recently developed for New York and California (Jacobson et al., 2013; 2014a). Such methods are applied here to make detailed, original, state-by-state estimates of

(1) Future energy demand (load) in the electricity, transportation, heating/cooling, and industrial sectors in both a business-as-usual (BAU) case and a WWS case;
(2) The numbers of WWS generators needed to meet the estimated load in each sector in the WWS case;
(3) Footprint and spacing areas needed for WWS generators;
(4) Rooftop areas and solar photovoltaic (PV) installation potentials over residential and commercial/government buildings and associated carports, garages, parking lots, and parking structures;
(5) The levelized cost of energy today and in 2050 in the BAU and WWS cases;
(6) Reductions in air-pollution mortality and associated health costs today based on pollution data from all monitoring stations in each state and in 2050, accounting for future reductions in emissions in the BAU versus WWS cases;
(7) Avoided global-warming costs today and in 2050 in the BAU versus WWS cases; and
(8) Numbers of jobs produced and lost and the resulting revenue changes between the BAU and WWS cases.

This paper further provides a transition timeline, energy efficiency measures, and potential policy measures to implement the plans. In sum, whereas, many studies focus on changing energy sources in one energy sector, such as electricity, this study integrates changes among all energy sectors: electricity, transportation, heating/cooling, and industry. It further provides rigorous and detailed and consistent estimates of 2050 state-by-state air pollution damage, climate damage, energy cost, solar rooftop potential, and job production and loss not previously available.

2. WWS Technologies

This study assumes all energy sectors are electrified by 2050. The WWS energy technologies chosen to provide electricity include wind, concentrated solar power (CSP), geothermal, solar PV, tidal, wave, and hydroelectric power. These generators are existing technologies that were found to reduce health and climate impacts the most among multiple technologies while minimizing land and water use and other impacts (Jacobson, 2009).

The technologies selected for ground transportation, which will be entirely electrified, include battery electric vehicles (BEVs) and hydrogen fuel cell (HFC) vehicles, where the hydrogen is produced by electrolysis. BEVs with fast charging or battery swapping will dominate long-distance, light-duty transportation; Battery electric-HFC hybrids will dominate heavy-duty transportation and long-distance shipping; batteries will power short-distance shipping (e.g., ferries); and electrolytic cryogenic hydrogen with batteries for idling, taxiing, and internal power will power aircraft.

Air heating and cooling will be electrified and powered by electric heat pumps (ground-, air-, or water-source) and some electric-resistance heating. Water heat will be generated by heat pumps with electric resistance elements and/or solar hot water preheating. Cook stoves will have either an electric induction or resistance-heating element.

High-temperature industrial processes will be powered by electric arc furnaces, induction furnaces, dielectric heaters, and resistance heaters and some combusted electrolytic hydrogen.

HFCs will be used only for transportation, not for electric power generation due to the inefficiency of that application for HFCs. Although electrolytic hydrogen for transportation is less efficient and more costly than is electricity for BEVs, some segments of transportation (e.g., long-distance ships and freight) may benefit from HFCs.

The roadmaps presented here 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). Biofuels, for example, are not included because their combustion produces air pollution at rates on the same order as fossil fuels and their lifecycle carbon emissions are highly uncertain but definitely larger than those of WWS technologies. Several biofuels also have water and land requirements much larger than those of WWS technologies. Since photosynthesis is 1% efficient whereas solar PV, for example, is ~20% efficient, the same land used for PV produces ~20 times more energy than a biofuel.

This study calculates the installed capacity and number of generators of each type needed in each state to potentially meet the state's *annual* power demand (assuming state-specific average-annual capacity factors) in 2050 after all sectors have been electrified, without considering sub-annual (e.g., daily or hourly) load balancing. The calculations assume only that existing hydroelectric from outside of a state continues to come from outside. The study then provides the additional number of generators needed by state to ensure that hourly power demand across all states does not suffer loss of load, based on results from Jacobson et al. (2015). As such, while the study bases each state's installed capacity on the state's annual demand, it allows interstate transmission of power as needed to ensure that supply and demand balance every hour in every state. (We also make a rough estimate of the cost of additional transmission lines needed for this hourly balancing.) Note that if we relaxed our assumption that each state's capacity match its annual demand, and instead allowed states with especially good solar or wind resources to have enough capacity to supply larger regions, then the average levelized cost of electricity would be lower than we estimate, because of the higher average capacity factors in states with the best WWS resources.

3. Changes in U.S. Power Load upon Conversion to WWS

Table 1 summarizes the state-by-state end-use load calculated by sector in 2050 if conventional fuel use continues along BAU or "conventional energy" trajectory. It also shows the estimated new load upon a conversion to a 100% WWS infrastructure (zero fossil fuels, biofuels, or nuclear fuels). The table is derived from a spreadsheet analysis of annually averaged end-use load data (Delucchi et al., 2015). All end uses that feasibly can be electrified are assumed to use WWS power directly, and remaining end uses (some heating, high-temperature industrial processes, and some transportation) are 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.

With these roadmaps, electricity generation increases, 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 less than the decrease in energy in the gas, liquid, and solid fuels that the electricity replaces, because of the high energy-to-work conversion efficiency of electricity used for heating and electric motors. As a result, end use load decreases significantly with WWS energy systems in all 50 states (Table 1).

Table 1. 1st row of each state: estimated 2050 total end-use load (GW) and percent of total load 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 load (GW) and percent of total load by sector if 100% of BAU end-use all-purpose delivered load in 2050 is instead provided by WWS. The estimate in the "% Change" column for each state is the percent reduction in total 2050 BAU load due to switching to WWS, including (second-to-last column) the effects of assumed policy-based improvements in end-use efficiency, inherent reductions in energy use due to electrification, and the elimination of energy use for the upstream production of fuels (e.g., petroleum refining). The number in the last column is the reduction due only to assumed, policy-driven end-use energy efficiency measures.

State	Scen-ario	2050 Total end-use load (GW)	Residential percent of total	Commercial percent of total	Industrial percent of total	Transport percent of total	% Change in end-use power with WWS	
							Overall	Effic. only
Alabama	BAU	53.9	11.3	9.3	51.2	28.2		
	WWS	35.3	13.5	11.2	60.4	14.9	-34.4	-4.5
Alaska	BAU	24.0	4.9	7.8	56.4	30.9		
	WWS	14.5	5.6	10.9	66.2	17.2	-39.8	-3.0
Arizona	BAU	38.0	20.7	18.9	15.5	44.9		
	WWS	21.9	28.7	25.4	19.0	27.0	-42.2	-10.5
Arkansas	BAU	31.6	14.8	13.0	38.8	33.4		
	WWS	20.3	18.2	16.5	47.4	17.8	-35.5	-4.5
California	BAU	229.3	13.2	14.6	26.9	45.3		
	WWS	127.8	16.9	22.2	34.3	26.6	-44.3	-7.1
Colorado	BAU	46.5	18.2	14.2	34.6	33.0		
	WWS	27.9	23.0	18.5	39.2	19.3	-40.1	-9.1

Connecticut	BAU	19.2	24.1	22.6	14.7	38.6		
	WWS	11.4	29.0	30.6	17.5	22.8	-40.7	-9.6
Delaware	BAU	5.9	19.5	23.2	23.4	33.9		
	WWS	3.5	24.2	30.6	27.2	18.0	-41.1	-10.5
Florida	BAU	107.2	19.5	18.2	16.9	45.4		
	WWS	61.2	26.9	24.7	22.4	25.9	-42.9	-9.8
Georgia	BAU	79.4	16.7	14.3	30.7	38.2		
	WWS	47.2	20.6	18.7	39.9	20.8	-40.6	-8.3
Hawaii	BAU	7.4	7.1	13.6	22.1	57.2		
	WWS	3.8	10.3	22.1	32.6	35.0	-49.5	-6.6
Idaho	BAU	15.0	17.5	12.9	36.0	33.6		
	WWS	9.5	21.8	15.9	42.9	19.5	-37.0	-7.8
Illinois	BAU	93.5	16.9	17.2	36.7	29.1		
	WWS	57.9	20.2	21.4	42.3	16.2	-38.1	-8.1
Indiana	BAU	64.4	12.4	11.5	50.6	25.6		
	WWS	40.4	15.0	14.1	57.5	13.5	-37.2	-6.6
Iowa	BAU	42.7	10.0	10.4	57.7	21.9		
	WWS	30.6	10.9	11.5	67.3	10.3	-28.3	2.0
Kansas	BAU	30.1	14.0	12.1	44.8	29.1		
	WWS	18.8	17.5	15.5	49.9	17.1	-37.5	-7.0
Kentucky	BAU	46.5	11.9	10.0	47.2	31.0		
	WWS	28.5	14.6	12.8	55.6	17.0	-38.8	-7.6
Louisiana	BAU	147.7	4.9	3.8	73.4	18.0		
	WWS	92.7	6.2	4.8	78.3	10.7	-37.2	-3.4
Maine	BAU	13.5	12.1	11.4	49.6	27.0		
	WWS	9.1	13.3	13.4	60.1	13.2	-32.7	-2.1
Maryland	BAU	34.9	20.9	25.9	14.1	39.1		
	WWS	20.1	25.9	34.8	16.6	22.7	-42.3	-11.4
Massachusetts	BAU	35.8	24.9	20.4	17.8	36.9		
	WWS	21.4	29.1	27.9	22.4	20.6	-40.3	-8.9
Michigan	BAU	64.8	19.3	19.5	28.2	33.0		
	WWS	39.9	22.9	24.5	33.8	18.7	-38.4	-9.4
Minnesota	BAU	48.8	14.8	14.5	41.1	29.6		
	WWS	31.5	17.7	17.9	48.9	15.5	-35.4	-4.0
Mississippi	BAU	33.9	10.5	9.5	44.1	35.8		
	WWS	21.0	13.1	12.1	53.7	21.0	-38.0	-6.3
Missouri	BAU	42.8	20.9	16.9	23.6	38.6		
	WWS	25.5	27.8	22.6	28.7	21.0	-40.4	-7.3
Montana	BAU	12.3	15.5	15.4	34.8	34.3		
	WWS	7.4	19.8	19.8	39.3	21.1	-39.5	-8.2
Nebraska	BAU	21.9	12.2	12.3	50.4	25.1		
	WWS	15.5	13.6	13.9	60.5	12.1	-29.3	0.4
Nevada	BAU	18.5	20.3	17.0	23.4	39.3		
	WWS	11.0	26.7	22.2	29.2	21.8	-40.6	-9.2
New Hampshire	BAU	7.1	20.9	19.0	17.9	42.3		
	WWS	3.9	27.4	26.9	21.7	24.0	-44.2	-8.7
New Jersey	BAU	57.5	17.7	23.3	17.0	42.0		
	WWS	32.9	22.7	33.9	19.6	23.7	-42.8	-7.1
New Mexico	BAU	21.6	12.9	13.6	40.3	33.2		
	WWS	12.8	16.9	17.9	45.3	19.9	-41.0	-8.8
New York	BAU	86.3	23.0	30.1	15.0	31.8		
	WWS	54.9	26.5	39.0	16.6	17.9	-36.4	-7.8
North Carolina	BAU	62.7	19.8	18.9	25.8	35.5		
	WWS	37.9	24.8	24.2	32.1	18.9	-39.5	-9.8
North Dakota	BAU	14.3	7.3	8.7	59.0	24.9		

	WWS	9.0	9.1	11.0	64.4	15.5	-36.9	-4.6
Ohio	BAU	87.0	16.2	16.4	37.6	29.8		
	WWS	53.5	19.8	20.5	43.6	16.1	-38.5	-8.2
Oklahoma	BAU	47.3	13.1	11.4	41.1	34.4		
	WWS	29.1	16.7	15.0	47.0	21.3	-38.5	-6.9
Oregon	BAU	27.3	15.4	15.6	26.5	42.6		
	WWS	16.3	18.9	21.9	34.6	24.6	-40.4	-8.5
Pennsylvania	BAU	94.0	15.4	14.1	39.5	31.0		
	WWS	59.1	18.5	18.3	44.1	19.2	-37.2	-7.3
Rhode Island	BAU	5.5	24.2	21.1	19.9	34.9		
	WWS	3.2	28.9	28.9	21.7	20.5	-41.5	-10.7
South Carolina	BAU	39.7	15.1	13.0	36.3	35.6		
	WWS	24.2	19.0	16.6	45.8	18.6	-39.1	-7.8
South Dakota	BAU	10.6	10.6	11.1	50.4	28.0		
	WWS	7.5	11.8	12.5	61.9	13.9	-29.1	1.8
Tennessee	BAU	52.8	15.6	13.5	36.5	34.3		
	WWS	32.2	19.6	17.4	44.5	18.4	-39.1	-7.3
Texas	BAU	376.6	8.4	8.0	56.9	26.7		
	WWS	225.3	11.2	10.8	62.7	15.3	-40.2	-4.8
Utah	BAU	23.2	17.8	16.6	28.7	36.8		
	WWS	13.8	22.8	21.8	33.0	22.4	-40.6	-9.1
Vermont	BAU	3.7	25.1	16.3	19.2	39.4		
	WWS	2.1	31.8	22.4	24.3	21.5	-42.7	-8.6
Virginia	BAU	60.3	18.0	20.3	23.1	38.6		
	WWS	35.1	22.7	27.1	28.5	21.7	-41.8	-10.2
Washington	BAU	52.8	14.3	15.2	30.2	40.4		
	WWS	31.7	17.7	21.3	38.7	22.4	-39.9	-7.4
West Virginia	BAU	21.7	14.3	12.3	40.6	32.7		
	WWS	13.0	17.0	15.9	45.3	21.7	-39.9	-12.3
Wisconsin	BAU	41.9	15.7	17.2	39.6	27.4		
	WWS	26.8	18.3	20.7	47.3	13.8	-36.0	-6.4
Wyoming	BAU	18.1	6.0	8.3	56.2	29.5		
	WWS	11.2	7.4	10.4	61.2	20.9	-38.3	-8.5
United States	BAU	2621.4	14.3	14.1	38.5	33.1		
	WWS	1591.0	17.8	18.6	45.0	18.6	-39.3	-6.9

BAU values are extrapolations from the U.S. Energy Information Administration (EIA) projections for the year 2040. WWS values are estimated with respect to BAU values accounting for the effect of electrification of end-uses on energy requirements and the effects of additional energy-efficiency measures. See the SI and Delucchi et al. (2015) for details.

In 2010, U.S. all-purpose, end-use load was ~2.37 TW (terawatts, or trillion watts). Of this, 0.43 TW (18.1%) was electric power load. 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, which involves growing load and modest shifts in the power sector away from coal to renewables and natural gas, all-purpose end-use load is expected to grow to 2.62 TW in 2050 (Table 1).

A conversion to WWS by 2050 is calculated here to reduce U.S. end-use load and the power required to meet that load by ~39.3% (Table 1). About 6.9 percentage points of this reduction is due to modest energy-conservation measures (Table 1, last column) and another relatively small portion is due to the fact that conversion to WWS reduces the need for energy use in petroleum 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. In Table 1, ~11.48% of all 2050 WWS electricity (47.8% of transportation load, and 5.72% of industrial load) will be used to produce, store, and use hydrogen, for long distance and heavy transportation and some high-temperature industrial processes.

The percent decrease in load upon conversion to WWS in Table 1 is greater in some states (e.g., Hawaii, California, Florida, New Jersey, New Hampshire, and Vermont) than in others (e.g. Minnesota, Iowa, and Nebraska). 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, and efficiency gains from electrifying transportation are much greater than are efficiency gains from electrifying other sectors.

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

Table 2 summarizes the number of WWS power plants or devices needed to power each U.S. state in 2050 for all purposes assuming end use power requirements in Table 1, the percent mix of end-use power generation in Table 3, and electrical transmission, distribution, and array losses. The specific mix of generators presented for each state in Table 3 is just one set of options.

Table 2. Number, capacity, footprint area, and spacing area of WWS power plants or devices needed to provide total annually-averaged end-use all-purpose load over all 50 states plus additional power needed to provide peaking and storage services, as derived in Jacobson et al. (2015). The numbers account for short- and moderate-distance transmission, distribution, forced and unforced maintenance, and array losses. Delucchi et al. (2015) derives individual tables for each state.

Energy Technology	Rated power one plant or device (MW)	[a]Percent of 2050 all-purpose load met by plant/device	Name-plate capacity of existing plus new plants or devices (MW)	Percent name-plate 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
Annual power							
Onshore wind	5	30.92	1,701,000	3.59	328,000	0.00004	1.5912
Offshore wind	5	19.08	780,900	0.00	156,200	0.00002	0.7578
Wave device	0.75	0.37	27,040	0.00	36,050	0.00021	0.0098
Geothermal plant	100	1.25	23,250	10.35	208	0.00078	0.0000
Hydroelectric plant[c]	1300	3.01	91,650	95.87	3	0.02077	0.0000
Tidal turbine	1	0.14	8,823	0.00	8,823	0.00003	0.0004
Res. roof PV	0.005	3.98	379,500	0.94	75,190,000	0.03070	0.0000

Com/gov roof PV [d]	0.1	3.24	276,500	0.64	2,747,000	0.02243	0.0000
Solar PV plant [d]	50	30.73	2,326,000	0.08	46,480	0.18973	0.0000
Utility CSP plant	100	7.30	227,300	0.00	2,273	0.12313	0.0000
Total		100.00	5,841,000	2.71		0.388	2.359
Peaking/storage							
Additional CSP [e]	100	4.38	136,400	0.00	1,364	0.07388	0.0000
Solar thermal [e]	50	7.21	469,000	0.00	9,380	0.00731	0.0000
Total all			6,447,000	2.46		0.469	2.359
Total new land[f]						0.416	1.591

The national total number of each device is the sum of among all states. The number of devices in each state is the end use load in 2050 in each state (Table 1) multiplied by the fraction of load satisfied by each source in each state (Table 3) and divided by the annual power output from each device. The annual output equals the rated power (this table; same for all states) multiplied by the state-specific annual capacity factor of the device and accounting for transmission, distribution, and array losses. The capacity factor is determined for each device in each state in Delucchi et al. (2015). The state-by-state capacity factors for onshore wind turbines in 2050, accounting for transmission, distribution, maintenance, and array losses, are calculated from actual 2013 state installed capacity (DOE, 2014) and power output (EIA, 2014e) with an assumed increase in capacity factor between 2013 and 2050 due to turbine efficiency improvements and a decrease due to diminishing quality of sites after the best are taken. The 2050 U.S. mean onshore wind capacity factor calculated in this manner (after transmission, distribution, maintenance-time, and array losses) is 29.0%. The highest state onshore wind capacity factor in 2050 is estimated to be 40.0%, for Oklahoma; the lowest, 17.0%, for Alabama, Kentucky, Mississippi, and Tennessee. Offshore wind turbines are 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, distribution, maintenance, and array losses of ~42.5% for the same turbine and 39.0%, in the U.S. average after losses. Short- and moderate distance transmission, distribution, and maintenance-time losses for offshore wind and all other energy sources treated here, except rooftop PV, are assumed to be 5-10%. Rooftop PV losses are assumed to be 1-2%. Wind array losses due to competition among turbines for the same energy are an additional 8.5% (Jacobson et al., 2015). The plans assume 38 (30-45)% of onshore wind and solar and 20 (15-25)% of offshore wind is subject to long-distance transmission with line lengths of 875 (750-1000) km and 75 (50-100) km, respectively. Line losses are 4 (3-5)% per 1000 km plus 1.5 (1.3-1.8)% of power in the station equipment. Footprint and spacing areas are calculated from the spreadsheets in Delucchi et al. (2015). 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 Delucchi et al. (2015). U.S. land area is 9,161,924 km^2.

[c] The average capacity factor for hydro is assumed to increase from its current value to 52.5% (see text). For hydro "already installed" capacity is based on data for 2010.

[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 Delucchi et al. (2015) 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 Delucchi et al. (2015).

[e] The installed capacities for peaking power/storage are derived in the grid integration study of Jacobson et al. (2015). Additional CSP is CSP plus storage beyond that needed for annual power generation to firm the grid across all states. Additional solar thermal is used for soil heat storage. Other types of storage are also used in Jacobson et al. (2015).

[f] 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 summarizes 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 are used to calculate potential rooftop generation, which in turn limits the penetration of residential and commercial/government PV in Table 3. Utility-scale 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 because it can take advantage of both direct and diffuse solar radiation, CSP is assumed to be viable only in states with sufficient direct solar radiation. While some states listed in Table 3, such as states in the upper Midwest, are assumed to install CSP although they have marginal average solar insolation, such states have regions with greater than average insolation, and the value of CSP storage is sufficiently high to suggest a small penetration of CSP in those states.

Onshore wind is assumed to be viable primarily in states with good wind resources (Section 5.1). Offshore wind is assumed to be viable offshore of any state with either ocean or Great Lakes coastline (Section 5.1). Wind and solar are the only two sources of electric power with sufficient resource to power the whole U.S. independently on their own. Averaged over the U.S., wind (~50.0%) and solar (45.2%) are the largest generators of annually averaged end-use electric power under these plans. The ratio of wind to solar end-use power is 1.1:1.

Under the roadmaps, the 2050 installed capacity of hydroelectric, averaged over the U.S., is assumed to be virtually the same as in 2010, except for a 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 2 lists installed capacities beyond those needed to match annually averaged power demand for CSP with storage and for solar thermal. These additional capacities are derived in the grid integration study of Jacobson et al. (2015) and are needed to produce peaking power, to account for additional loads due to losses in and out of storage, and to ensure reliability of the grid, as described and quantified in that paper.

Table 3. Percent of annually-averaged 2050 U.S. state all-purpose end-use load 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. All rows add up to 100%.

State	Onshore wind	Offshore wind	Wave	Geoth-ermal	Hydro-electric	Tidal	Res PV	Comm/ gov PV	Utility PV	CSP
Alabama	5.00	10.00	0.08	0.00	4.84	0.01	3.50	2.20	64.38	10.00
Alaska	50.00	20.00	1.00	7.00	14.96	1.00	0.23	0.15	5.66	0.00
Arizona	18.91	0.00	0.00	2.00	6.49	0.00	1.30	9.30	32.00	30.00
Arkansas	43.00	0.00	0.00	0.00	3.44	0.00	4.40	3.50	35.66	10.00
California	25.00	10.00	0.50	5.00	4.48	0.50	7.50	5.50	26.52	15.00
Colorado	55.00	0.00	0.00	3.00	1.24	0.00	4.20	4.00	17.56	15.00
Connecticut	5.00	45.00	1.00	0.00	0.56	0.00	4.00	3.35	41.09	0.00
Delaware	5.00	65.00	1.00	0.00	0.00	0.50	5.00	3.85	19.65	0.00
Florida	5.00	14.93	1.00	0.00	0.05	0.04	11.2	7.80	49.98	10.00
Georgia	5.00	35.00	0.30	0.00	2.27	0.08	5.50	4.30	42.55	5.00
Hawaii	12.00	16.00	1.00	30.00	0.33	1.00	14.0	9.00	9.67	7.00
Idaho	35.00	0.00	0.00	15.00	14.96	0.00	4.00	3.20	17.84	10.00
Illinois	60.00	5.00	0.00	0.00	0.03	0.00	2.85	2.90	26.22	3.00
Indiana	50.00	0.00	0.00	0.00	0.08	0.00	2.45	2.20	42.77	2.50
Iowa	68.00	0.00	0.00	0.00	0.25	0.00	1.50	1.50	25.75	3.00
Kansas	70.00	0.00	0.00	0.00	0.01	0.00	3.20	3.00	13.79	10.00
Kentucky	8.45	0.00	0.00	0.00	1.51	0.00	3.20	2.10	79.74	5.00
Louisiana	0.65	60.00	0.40	0.00	0.11	0.00	1.30	1.20	31.34	5.00
Maine	35.00	35.00	1.00	0.00	5.79	1.00	5.40	1.80	15.01	0.00
Maryland	5.00	60.00	1.00	0.00	1.53	0.03	5.40	4.80	22.24	0.00
Massachusetts	13.00	55.00	1.00	0.00	1.42	0.06	3.90	3.30	22.32	0.00
Michigan	40.00	31.00	1.00	0.00	0.69	0.00	3.50	3.20	18.61	2.00
Minnesota	60.00	19.00	0.00	0.00	3.61	0.00	2.50	3.00	9.89	2.00
Mississippi	5.00	10.00	1.00	0.00	0.00	1.00	2.40	1.60	74.00	5.00
Missouri	60.00	0.00	0.00	0.00	1.15	0.00	5.10	4.40	24.35	5.00
Montana	35.00	0.00	0.00	9.00	19.15	0.00	2.80	2.10	21.95	10.00
Nebraska	65.00	0.00	0.00	0.00	0.94	0.00	2.20	2.00	19.86	10.00
Nevada	10.00	0.00	0.00	30.00	5.02	0.00	12.0	8.00	19.23	15.75
New Hampshire	40.00	20.00	1.00	0.00	6.48	0.50	4.50	3.30	24.22	0.00
New Jersey	10.00	55.50	0.80	0.00	0.01	0.10	3.54	2.80	27.25	0.00
New Mexico	50.00	0.00	0.00	10.00	0.35	0.00	5.50	3.80	14.35	16.00
New York	10.00	40.00	0.80	0.00	6.54	0.10	3.60	3.20	35.76	0.00
North Carolina	5.00	50.00	0.75	0.00	2.69	0.03	6.00	4.00	26.53	5.00
North Dakota	55.00	0.00	0.00	0.00	2.95	0.00	1.00	1.00	35.05	5.00
Ohio	45.00	10.00	0.00	0.00	0.10	0.00	3.20	3.00	35.70	3.00
Oklahoma	65.00	0.00	0.00	0.00	1.54	0.00	3.20	2.80	17.46	10.00
Oregon	32.50	15.00	1.00	5.00	27.25	0.05	4.00	2.20	8.00	5.00
Pennsylvania	20.00	3.00	1.00	0.00	0.74	0.85	3.30	2.35	68.76	0.00
Rhode Island	10.00	63.00	1.00	0.00	0.05	0.08	4.40	3.70	17.78	0.00
South Carolina	5.00	50.00	1.00	0.00	2.90	0.30	4.00	2.80	27.70	6.30
South Dakota	61.00	0.00	0.00	0.00	11.10	0.00	1.70	1.80	14.40	10.00
Tennessee	8.00	0.00	0.00	0.00	4.26	0.00	3.50	2.20	75.04	7.00
Texas	50.00	13.90	0.10	0.50	0.16	0.00	3.00	2.50	15.84	14.00
Utah	40.00	0.00	0.00	8.00	1.03	0.00	4.00	4.00	27.97	15.00
Vermont	25.00	0.00	0.00	0.00	64.35	0.00	4.20	2.80	3.65	0.00
Virginia	10.00	50.00	0.50	0.00	1.29	0.05	4.20	3.50	25.46	5.00
Washington	35.00	13.00	0.50	0.65	35.42	0.30	2.90	1.50	10.73	0.00
West Virginia	30.00	0.00	0.00	0.00	1.14	1.00	2.50	1.70	61.66	2.00
Wisconsin	45.00	30.00	0.00	0.00	0.96	0.00	3.30	2.90	15.84	2.00

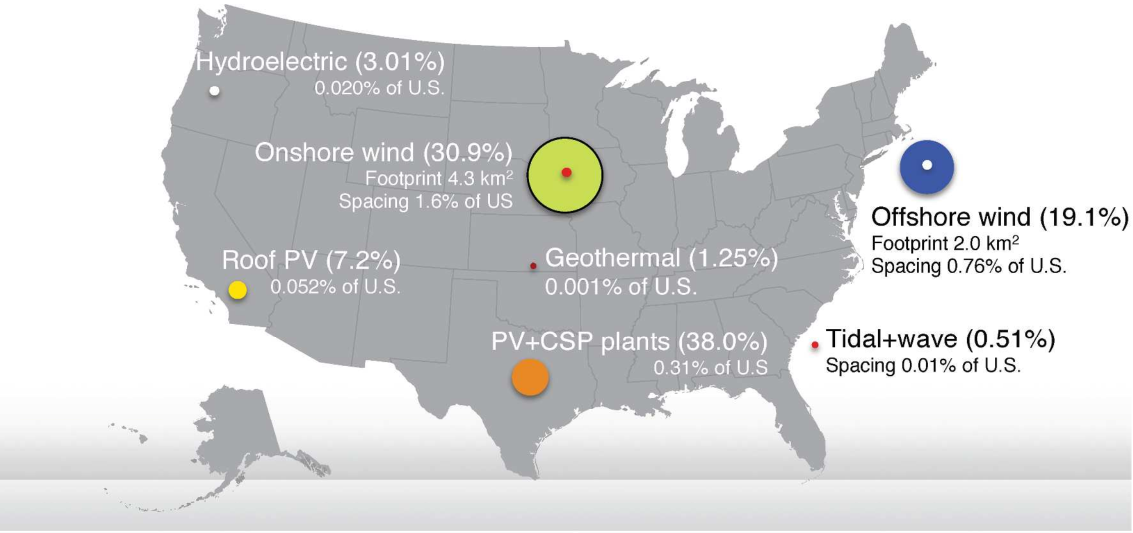
Wyoming	65.00	0.00	0.00	1.00	1.43	0.00	1.10	0.70	20.77	10.00
United States	30.92	19.08	0.37	1.25	3.01	0.14	3.98	3.24	30.73	7.30

Figure 1 shows the additional footprint and spacing areas required from Table 2 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 ~0.42% 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, which includes 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 ~1.6% of U.S. land. The footprint associated with this 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. Spacing and footprint areas required from Table 2, beyond existing 2013 resources, 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

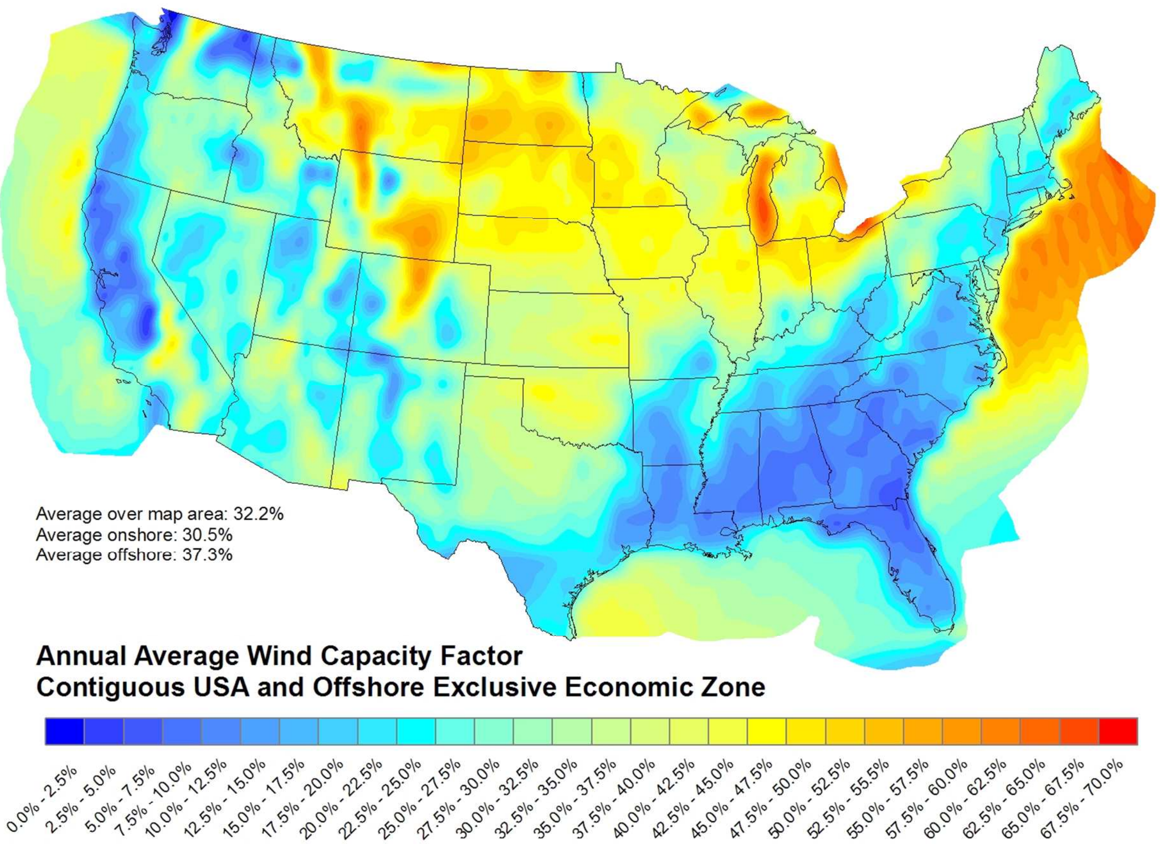
This section evaluates whether the United States has sufficient wind, solar, geothermal, and hydroelectric resources to supply the country's all-purpose energy in 2050.

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 are installed onshore and offshore. The calculations are performed assuming a REpower 5 MW turbine with a 126-m diameter rotor (the same turbine assumed for the roadmaps). Results are obtained for a hub height of 100-m above the topographical surface. Spacing areas of 4x7 rotor diameters are used for onshore turbines and 5x10 diameters for offshore turbines.

Results suggest a U.S. mean onshore capacity factor of ~30.5% and offshore of ~37.3% before transmission, distribution, maintenance-time, and array losses (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 ~1.6% of U.S. onshore land and 0.76% of U.S. onshore-equivalent land area sited offshore for wind-turbine spacing to power 50.0% of all-purpose annually-averaged 2050 U.S. energy. The mean capacity factor before transmission, distribution, maintenance time, and array losses used to derive the number of onshore wind turbines needed in Table 2 is ~35% and for offshore turbines 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 roadmaps.

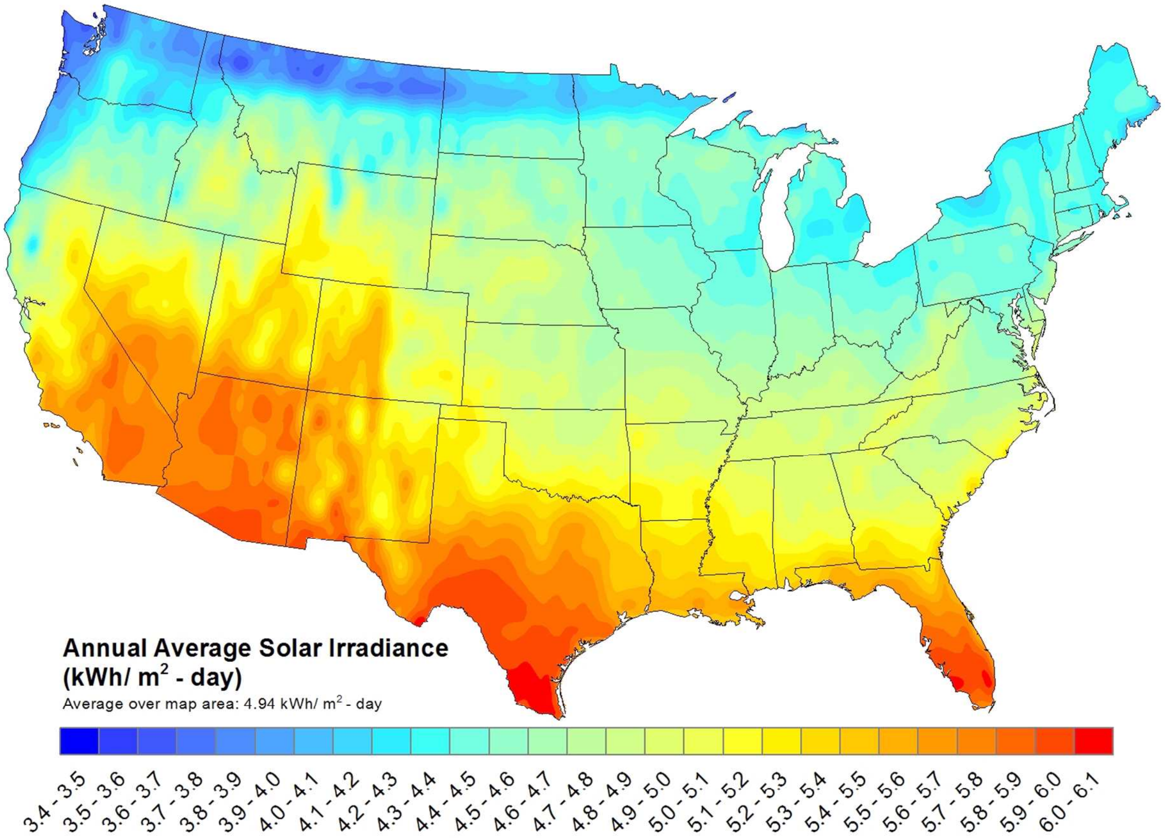
Figure 2. Modeled 2006 annually averaged capacity factor for 5 MW REpower wind turbines (126-m diameter rotor) at 100-m hub height above the topographical surface in the contiguous United States ignoring competition among wind turbines for the same kinetic energy and before transmission, distribution, and maintenance-time losses. The model used is GATOR-GCMOM (Jacobson et al., 2007; Jacobson, 2010), which is nested for one year from the global to regional scale with resolution on the regional scale of 0.6^o W-E x 0.5^o S-N.



5.2. Solar

World solar power resources are known to be large (e.g., Darling and You, 2013). Here, such resources are estimated (Figure 3) for the U.S. using a 3-D climate model that treats radiative transfer 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 ~0.394% of U.S. land area, which is a small percentage of the area of strong solar resources available (Figure 3).

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 is 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 is nested from the global to regional scale with resolution on the regional scale 0.6^o W-E x 0.5^o S-N.



The estimates of potential generation by solar rooftop PV shown in Tables 2 and 3 are based on state-by-state calculations of available roof areas and PV power potentials on residential, commercial, and governmental buildings, garages, carports, parking lots, and parking structures. Commercial and governmental buildings include all non-residential buildings except manufacturing, industrial, and military buildings. (Commercial buildings do include schools.)

Jacobson et al. (2014, Supplemental Information) and Delucchi et al. (2015) document how rooftop areas and generation potential are calculated for California for four situations: residential-warm, residential-cool, commercial/government-warm, and commercial/government-cool. This method is applied here to calculate potential rooftop PV generation in each state, accounting for housing units and building areas, available solar insolation , degradation of solar panels over time, technology improvements over time, and DC to AC power conversion losses.

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 under the four situations mentioned above: residential and commercial/government rooftop PV systems, in warm and cool climate zones.

Based on the analysis, we estimate that, in 2050, residential rooftop areas (including garages and carports) could support 660 $\mathrm{GW}_{\text{dc-peak}}$ of installed power. The plans here propose to install ~57% of this potential. In 2050, commercial/government rooftop areas (including parking lots and parking structures) could support 505 $\mathrm{GW}_{\text{dc-peak}}$ of installed power. The state plans here propose to cover ~55% of installable power.

Table 4. Rooftop areas suitable for PV panels, potential capacity of suitable rooftop areas, and proposed installed capacity for both residential and commercial/government buildings, by state. See Delucchi et al. (2015) for detailed calculations.

	Residential rooftop PV				Commercial/government rooftop PV			
State	Rooftop area suitable for PVs in 2012 (km^2)	Potential capacity of suitable area in 2050 ($\mathrm{MW}_{\text{dc-peak}}$)	Proposed installed capacity in 2050 ($\mathrm{MW}_{\text{dc-peak}}$)	Percent of potential capacity installed	Rooftop area suitable for PVs in 2012 (km^2)	Potential capacity of suitable area in 2050 ($\mathrm{MW}_{\text{dc-peak}}$)	Proposed installed capacity in 2050 ($\mathrm{MW}_{\text{dc-peak}}$)	Percent of potential capacity installed
Alabama	59.7	10,130	7,409	73	35.4	6,150	4,175	68
Alaska	7.0	760	414	54	4.2	460	242	53
Arizona	7.1	3,520	1,379	39	46.9	23,210	8,841	38
Arkansas	36.7	7,090	5,217	74	27.0	5,330	3,720	70
California	336.1	83,150	48,412	58	220.6	55,330	31,826	58
Colorado	48.8	11,190	6,684	60	40.6	9,440	5,706	60
Connecticut	32.2	4,640	3,301	71	25.1	3,690	2,478	67
Delaware	10.9	1,940	1,182	61	7.3	1,320	816	62
Florida	229.1	85,950	33,873	39	148.4	55,750	21,147	38
Georgia	108.9	25,760	15,431	60	76.9	18,450	10,815	59
Hawaii	12.7	3,260	2,291	70	7.5	1,950	1,320	68
Idaho	16.2	4,030	2,318	58	12.2	3,070	1,663	54
Illinois	116.3	17,220	11,537	67	110.6	16,770	10,524	63
Indiana	65.6	10,500	6,652	63	54.8	8,960	5,354	60
Iowa	31.2	4,430	3,165	71	29.4	4,260	2,837	67
Kansas	32.1	5,220	3,804	73	28.1	4,680	3,197	68
Kentucky	52.7	8,270	6,076	73	32.3	5,200	3,575	69
Louisiana	54.2	9,910	6,582	66	44.6	8,350	5,447	65
Maine	32.2	4,740	3,340	70	9.4	1,410	998	71
Maryland	60.5	11,550	7,102	61	49.0	9,530	5,659	59
Massachusetts	58.6	8,560	6,053	71	46.4	6,930	4,591	66
Michigan	105.0	14,970	10,142	68	89.0	12,980	8,312	64
Minnesota	52.9	9,280	5,564	60	54.6	9,740	5,985	61
Mississippi	35.5	4,950	3,653	74	22.6	3,230	2,183	68
Missouri	72.9	12,260	8,270	67	58.0	9,980	6,396	64
Montana	11.6	1,880	1,391	74	8.2	1,350	936	69
Nebraska	20.5	3,140	2,228	71	18.0	2,830	1,816	64
Nevada	29.4	15,120	6,451	43	18.8	9,600	3,855	40
New Hampshire	13.9	2,480	1,287	52	9.3	1,680	846	50
New Jersey	83.1	12,730	8,345	66	60.7	9,520	5,917	62
New Mexico	24.7	5,070	3,674	72	15.7	3,300	2,276	69
New York	165.2	20,140	14,545	72	135.0	16,940	11,590	68
North Carolina	119.2	28,340	14,084	50	74.6	17,950	8,417	47
North Dakota	7.2	940	639	68	6.8	920	573	62
Ohio	117.0	16,960	11,623	69	101.0	15,000	9,768	65

Oklahoma	46.2	8,150	5,544	68	34.8	6,270	4,349	69
Oregon	43.5	8,590	4,431	52	21.6	4,330	2,185	50
Pennsylvania	136.4	18,870	13,757	73	87.9	12,410	8,782	71
Rhode Island	9.9	1,460	1,015	70	7.8	1,180	765	65
South Carolina	58.4	9,220	6,057	66	36.8	5,950	3,801	64
South Dakota	8.5	1,290	857	66	8.3	1,280	813	64
Tennessee	76.6	12,020	7,246	60	45.9	7,370	4,083	55
Texas	268.9	78,190	36,792	47	216.9	63,550	27,485	43
Utah	23.1	6,360	3,160	50	20.9	5,810	2,833	49
Vermont	7.5	1,110	672	61	4.5	680	402	59
Virginia	88.1	17,400	9,825	56	65.8	13,190	7,339	56
Washington	73.6	14,050	6,774	48	37.2	7,180	3,141	44
West Virginia	24.3	3,140	2,273	72	16.1	2,140	1,386	65
Wisconsin	59.5	9,310	6,236	67	48.3	7,710	4,912	64
Wyoming	6.3	1,050	754	72	4.5	760	430	57
United States	3197.6	660,290	379,513	57	2,386	505,070	276,508	55

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).

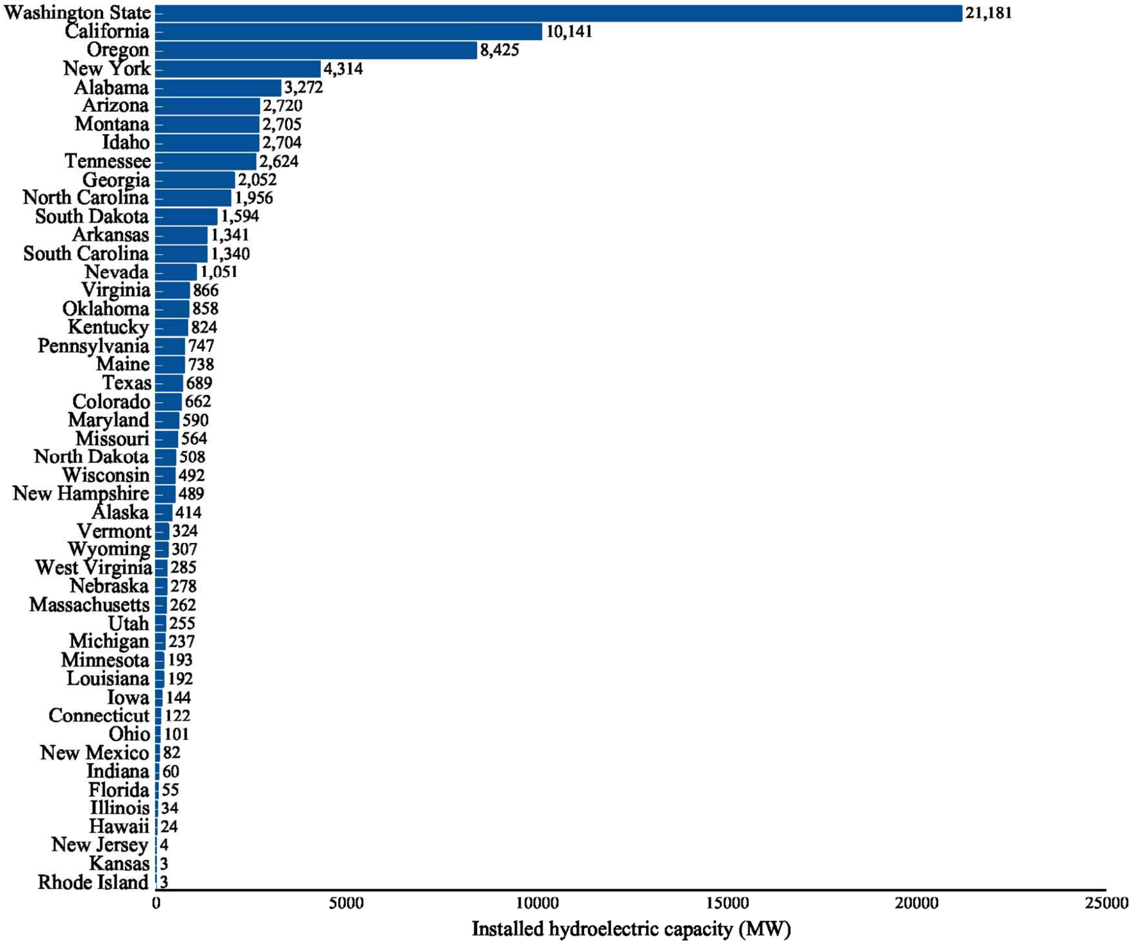
States with identified geothermal resources (and the percent of resource available in each state) include Colorado (0.33%), Hawaii (2.0%), Idaho (3.68%), Montana (0.65%), Nevada (15.36%), New Mexico (1.88%), Oregon (5.96%), Utah (2.03%), Washington State (0.25%), Wyoming (0.43%), Alaska (7.47%), Arizona (0.29%), and California (59.67%) (USGS, 2008). All states have the ability to extract heat from the ground for heat pumps. This extracted energy would not be used to generate electricity, but rather would be used directly for heating, thereby reducing electric power demand for heating, although electricity would still be needed to run heat pumps). (This electricity use for heat pumps is accounted for in the numbers for Table 1.)

The roadmaps here propose 19.8 GW of delivered existing plus new electric power from geothermal in 2050, which is 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 with known resources plus Texas, where recent studies show several potential sites for geothermal. If resources in other states prove to be cost-effective, these roadmaps can be updated to include geothermal in those states.

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, 2012). The installed conventional hydroelectric capacity was 78.825 GW (EIA, 2012), giving the capacity factor of conventional hydro as 37.7% in 2010. Figure 4 shows the installed conventional hydroelectric by state in 2010.

Figure 4. Installed conventional hydroelectric by U.S. state in 2010 (EIA, 2012).



In addition, 23 U.S. states receive an estimated 5.103 GW of delivered hydroelectric power from Canada. Assuming a capacity factor of 56.47%, Canadian hydro currently provides ~9.036 GW worth of installed capacity to the U.S. This is included as part of existing hydro capacity in this study to give a total existing (year-2010) capacity in the U.S. in Table 2 of 87.86 GW.

Under the plan proposed here, conventional hydro would supply 3.01% of U.S. total end-use all-purpose power demand (Table 2), or 47.84 GW of delivered power in 2050. In 2010, U.S. plus Canadian delivered 34.8 GW of hydropower, only 13.0 GW less than that needed in 2050. This additional power will be supplied by adding three new dams in Alaska with a total capacity of 3.8 GW (Table 2) and increasing the capacity factor on existing dams from a Canada-plus-US average of ~39% to 52.5%. Increasing the capacity factor is feasible because existing dams currently provide much less than their maximum capacity, primarily due to an oversupply of energy available from fossil fuel sources, resulting in less demand for hydroelectricity. In some cases, hydroelectricity is not used to its full extent in deference to other priorities affecting water use.

Whereas, we believe modestly increasing hydroelectric capacity factors is possible, if it is not, additional hydroelectric capacity can be obtained by powering presently non-powered dams. In addition to the 2,500-plus dams that provide the 78.8 GW of installed conventional power and 22.2 GW of installed pumped-storage hydroelectric power, the U.S. has over 80,000 dams that are not powered at present. Although only a small fraction of these dams can feasibly be powered, DOE (2012) estimates that the potential amounts to 12 GW of capacity in the contiguous 48 states. Two-thirds of this comes from just 100 dams, but potential exists in every state. Over 80% of the top 100 dams with the most new-powering 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 – far more than the 11.3 GW of additional generation proposed here. 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 contribute about 0.14% 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 ~2.2 GW of delivered power, which would require an installed capacity of ~8.82 GW of tidal turbines.

5.6. Wave

Wave power is proposed to contribute 0.37%, or about 5.85 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 ~23 times the delivered power proposed under this plan.

6. Matching Electric Power Supply with Demand

Jacobson et al. (2015) develop and apply a grid integration model to determine the quantities and costs of additional storage devices and generators needed to ensure that the 100% WWS system developed here for the U.S. can match load without loss every 30 s for six years (2050-2055) while accounting for the variability and uncertainty in WWS resources. Wind and solar time-series are derived from 3-D global model simulations that account for extreme events, competition among wind turbines for kinetic energy, and the feedback of extracted solar radiation to roof and surface temperatures.

Solutions to the grid integration problem are obtained by prioritizing storage for excess heat (in soil and water) and electricity (in ice, water, phase-change material tied to CSP, pumped hydro, and hydrogen); using hydroelectric only as a last resort; and using demand response to shave periods of excess demand over supply. No batteries (except in electric vehicles), biomass, nuclear power, or natural gas are needed. Frequency regulation of the grid is proposed to be provided by ramping up/down hydroelectric, stored CSP or pumped hydro; ramping down other WWS generators and storing the electricity in heat, cold, or hydrogen instead of curtailment; and using demand response.

The study is able to derive multiple low-cost stable solutions with the number of generators across the U.S. listed in Table 2 here, except that that study applies to the continental U.S., so excludes data for Alaska and Hawaii. Numerous low-cost solutions are found, suggesting that maintaining grid reliability upon 100% conversion to WWS is economically feasible and not a barrier to the conversion.

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. These costs do not include the costs of storage necessary to keep the grid stable, which are quantified in Jacobson et al. (2015). The estimates here are based on current cost data and trend projections for individual generator types and do not account for interactions among energy generators and major end uses (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 5 presents 2013 and 2050 U.S. averaged estimates of fully annualized levelized business costs of electric power generation for conventional fuels and WWS technologies. Whereas, several studies have calculated levelized costs of present-day renewable energy (e.g., Lazard, 2014; Darling et al., 2015), few have estimated such costs in the future. The methodology used here for determining 2050 levelized costs is described in the Supplemental Information. The table indicates that the 2013 business costs of hydroelectric, onshore wind, utility-scale solar, and solar thermal for heat are already similar to or less than the costs of natural gas combined cycle. Residential and commercial rooftop PV, offshore wind, tidal, and wave are more expensive. However, residential rooftop PV costs are given as if PV is purchased for an individual household. A common business model today is where multiple households contract together with a solar provider, thereby decreasing the average cost.

By 2050, however, the costs of all WWS technologies are expected to drop, most significantly for offshore wind, tidal, wave, rooftop PV, CSP, and utility PV, whereas conventional fuel costs are expected to rise. Because WWS technologies have zero fuel costs, the drop in their costs over time is due primarily to technology improvements. In addition, WWS costs are expected to decline due to less expensive manufacturing and streamlined project deployment from increased economies of scale. Conventional fuels, on the other hand, face rising costs over time due to higher labor and transport costs for mining, transporting, and processing fuels continuously over the lifetime of fossil-fuel plants.

Table 5. Approximate fully annualized, unsubsidized 2013 and 2050 U.S.-averaged costs of delivered electricity, including generation, short- and long-distance transmission, distribution, and storage, but not including external costs, for conventional fuels and WWS power (2013 U.S. $/kWh-delivered).

Technology	**Technology year 2013**			**Technology year 2050**		
	LCHB	*HCLB*	*Average*	*LCHB*	*HCLB*	*Average*
Advanced pulverized coal	0.083	0.113	0.098	0.079	0.107	0.093
Advanced pulverized coal w/CC	0.116	0.179	0.148	0.101	0.151	0.126
IGCC coal	0.094	0.132	0.113	0.084	0.115	0.100
IGCC coal w/CC	0.144	0.249	0.197	0.098	0.146	0.122
Diesel generator (for steam turb.)	0.187	0.255	0.221	0.250	0.389	0.319
Gas combustion turbine	0.191	0.429	0.310	0.193	0.404	0.299
Combined cycle conventional	0.082	0.097	0.090	0.105	0.137	0.121
Combined cycle advanced	n.a.	n.a.	n.a.	0.096	0.119	0.108
Combined cycle advanced w/CC	n.a.	n.a.	n.a.	0.112	0.143	0.128
Fuel cell (using natural gas)	0.122	0.200	0.161	0.133	0.206	0.170
Microturbine (using natural gas)	0.123	0.149	0.136	0.152	0.194	0.173
Nuclear, APWR	0.082	0.143	0.112	0.073	0.121	0.097
Nuclear, SMR	0.095	0.141	0.118	0.080	0.114	0.097
Distributed gen. (using natural gas)	n.a.	n.a.	n.a.	0.254	0.424	0.339
Municipal solid waste	0.204	0.280	0.242	0.180	0.228	0.204
Biomass direct	0.132	0.181	0.156	0.105	0.133	0.119
Geothermal	0.087	0.139	0.113	0.081	0.131	0.106
Hydropower	0.063	0.096	0.080	0.055	0.093	0.074
On-shore wind	0.076	0.108	0.092	0.064	0.101	0.082
Off-shore wind	0.111	0.216	0.164	0.093	0.185	0.139
CSP no storage	0.131	0.225	0.178	0.091	0.174	0.132
CSP with storage	0.081	0.131	0.106	0.061	0.111	0.086
PV utility crystalline tracking	0.073	0.107	0.090	0.061	0.091	0.076
PV utility crystalline fixed	0.078	0.118	0.098	0.063	0.098	0.080
PV utility thin-film tracking	0.073	0.104	0.089	0.061	0.090	0.075
PV utility thin-film fixed	0.077	0.118	0.098	0.062	0.098	0.080
PV commercial rooftop	0.098	0.164	0.131	0.072	0.122	0.097
PV residential rooftop	0.130	0.225	0.177	0.080	0.146	0.113
Wave power	0.276	0.661	0.468	0.156	0.407	0.282
Tidal power	0.147	0.335	0.241	0.084	0.200	0.142
Solar thermal for heat ($/kWh-th)	0.057	0.070	0.064	0.051	0.074	0.063

LCHB = low cost, high benefits case; HCLB = high cost, low benefits case. The methodology for determining costs is given in the Supplemental Information.

For the year 2050 100% WWS scenario, costs are shown for WWS technologies; for the year 2050 BAU case, costs of WWS are slightly different. The costs assume $0.0115 (0.11-0.12)/kWh for standard (but not extralong-distance) transmission for all technologies except rooftop solar PV (to which no transmission cost is assigned) and \$0.0257 (0.025-0.0264)/kWh for distribution for all technologies. Transmission and distribution losses are accounted for in the energy available.

CC = carbon capture; IGCC = integrated gasification combined cycle; AWPR = advanced pressurized-water reactor; SMR = small modular reactor; PV = photovoltaics.

CSP w/storage assumes a maximum charge to discharge rate (storage size to generator size ratio) of 2.62:1.

Solar thermal for heat assumes \$3,600-\$4,000 per 3.716 m^2 collector and 0.7 kW-th/m^2 maximum power (Jacobson et al., 2015).

The 2050 U.S. air pollution cost (Table 7) plus global climate cost (Table 8) per unit total U.S. energy produced by the conventional fuel sector in 2050 (Table 1) corresponds to a mean 2050 externality cost (in 2013 dollars) due to conventional fuels of ~\$0.17 (0.085-0.41)/kWh. Such costs arise due to air pollution morbidity and mortality and global warming damage (e.g. coastline losses, fishery losses, heat stress mortality, increased drought and wildfires, and increased severe severe weather) caused by conventional fuels. When externality costs are added to the business costs of conventional fuels, all WWS technologies cost less than conventional technologies in 2050.

Table 6 provides the mean value of the 2013 and 2050 LCOEs for conventional fuels and the mean value of the LCOE of WWS fuels in 2050 by state. The table also gives the 2050 energy, health, and global climate cost savings per person. The electric power cost of WWS in 2050 is not directly comparable with the BAU electric power cost, because the latter does not integrate transportation, heating/cooling, or industry energy costs. Conventional vehicle fuel costs, for example, are a factor of 4-5 higher than those of electric vehicles, yet the cost of BAU electricity cost in 2050 does not include the transportation cost, whereas the WWS electricity cost does. Nevertheless, based on the comparison, WWS energy in 2050 will save the average U.S. consumer \$260 (190-320)//yr in energy costs (\$2013 dollars). In addition, WWS will save \$1,500 (210-6,000)/yr in health costs, and \$8,300 (4,700-17,600)/yr in global climate costs. The total up-front capital cost of the 2050 WWS system is ~\$13.4 trillion (~\$2.08 mil./MW).

Table 6. Mean values of the levelized cost of energy (LCOE) for conventional fuels in 2013 and 2050 and for WWS fuels in 2050. The LCOEs do not include externality costs. The 2013 and 2050 values are used to calculate energy cost savings per person per year in each state (see footnotes). Health and climate cost savings per person per year are derived from data in Section 8. All costs are in 2013 dollars. Low-cost and high-cost results can be found in the "Expanded cost results by state" tab in Delucchi et al. (2015).

State	(a) 2013 Average LCOE conven-tional fuels (¢/kWh)	(b) 2050 Average LCOE conven-tional fuels (¢/kWh)	(c) 2050 Average LCOE of WWS (¢/kWh)	(d) 2050 Average electricity cost savings per person per year (\$/per-son/yr)	(e) 2050 Average air quality damage savings per person per year due to WWS (\$/per-son/yr)	(f) 2050 Average climate cost savings to state per person per year due to WWS (\$/per-son/yr)	(g) 2050 Average climate cost savings to world per person per year due to WWS (\$/per-son/yr)	[h](h) 2050 Average energy + air quality damage + world climate cost savings due to WWS (\$/per-son/yr)
Alabama	11.4	10.7	8.7	693	1,464	1,808	15,046	17,203
Alaska	15.1	15.5	11.1	483	886	-1,042	25,692	27,060
Arizona	11.2	10.3	8.7	250	1,852	958	4,266	6,368

Arkansas	11.2	10.8	8.2	731	1,132	1,585	12,855	14,717
California	12.5	10.7	9.7	161	2,503	494	4,731	7,393
Colorado	9.9	9.9	8.5	312	1,033	-165	7,957	9,303
Connecticut	12.5	11.0	11.9	114	1,475	-215	5,359	6,948
Delaware	12.0	11.1	12.8	65	2,361	1,218	10,045	12,470
Florida	12.7	11.6	9.1	319	1,099	1,905	3,789	5,207
Georgia	11.4	10.7	10.1	293	1,568	1,045	7,198	9,059
Hawaii	22.7	30.3	11.9	1,785	1,028	2,176	8,762	11,575
Idaho	9.4	9.0	9.0	188	1,051	-349	4,228	5,468
Illinois	10.1	9.8	9.4	231	1,790	18	9,736	11,757
Indiana	10.6	10.4	9.3	436	1,922	129	16,770	19,128
Iowa	9.4	9.3	8.4	392	1,270	-903	17,063	18,726
Kansas	9.6	9.4	8.3	349	962	1,130	13,972	15,282
Kentucky	10.1	9.6	8.7	516	1,492	919	19,346	21,354
Louisiana	11.2	10.8	11.5	242	1,250	3,019	30,706	32,197
Maine	12.5	11.0	11.4	143	739	-1,713	8,029	8,912
Maryland	12.0	11.1	12.5	72	1,725	556	5,390	7,187
Massachusetts	12.5	11.0	12.7	26	1,148	-460	5,192	6,365
Michigan	10.6	10.8	11.4	157	1,280	-468	9,495	10,932
Minnesota	9.4	9.3	9.8	98	963	-299	8,074	9,134
Mississippi	11.2	10.8	9.5	531	1,357	1,975	12,125	14,013
Missouri	10.1	9.8	8.5	368	1,377	1,190	11,418	13,162
Montana	9.4	9.0	9.0	260	1,021	-564	19,245	20,526
Nebraska	9.4	9.3	8.3	382	973	-1,366	15,420	16,775
Nevada	9.4	9.0	9.4	98	1,628	589	4,110	5,836
New Hampshire	12.5	11.0	10.8	144	967	-880	5,621	6,732
New Jersey	12.0	11.1	12.4	57	1,272	675	6,174	7,504
New Mexico	11.2	10.3	9.2	437	1,230	523	18,095	19,762
New York	14.5	12.6	13.4	112	1,168	112	4,508	5,789
North Carolina	11.1	10.5	11.1	131	1,322	741	5,170	6,623
North Dakota	9.4	9.3	8.4	483	598	482	47,504	48,584
Ohio	10.6	10.4	9.6	369	1,834	55	12,065	14,268
Oklahoma	10.5	10.5	8.1	655	1,189	1,778	15,855	17,699
Oregon	9.4	9.0	10.0	33	894	-719	4,305	5,232
Pennsylvania	12.0	11.1	9.8	341	1,746	28	10,799	12,886
Rhode Island	12.5	11.0	12.8	48	1,144	-766	6,094	7,286
South Carolina	11.1	10.5	11.1	193	1,511	1,560	8,396	10,100
South Dakota	9.4	9.3	8.1	372	719	-653	9,972	11,063
Tennessee	10.1	9.6	8.6	338	1,620	1,119	7,576	9,534
Texas	10.7	10.7	8.7	384	1,267	1,456	10,273	11,923
Utah	9.4	9.0	8.9	127	1,640	93	8,405	10,173
Vermont	12.5	11.0	8.7	336	726	-1,392	4,933	5,995
Virginia	11.1	10.5	11.2	142	1,255	676	5,501	6,898
Washington	9.4	9.0	9.4	85	949	-635	4,195	5,229
West Virginia	10.6	10.4	9.2	703	1,259	172	38,911	40,873
Wisconsin	10.1	11.3	10.6	318	1,197	-548	9,264	10,779
Wyoming	9.9	9.9	8.3	1,382	787	-612	75,614	77,783
United States	11.11	10.55	9.78	263	1,491	661	8,265	10,019

a) The 2013 LCOE cost for conventional fuels in each state combines the estimated distribution of conventional and WWS generators in 2013 with 2013 mean LCOEs for each generator from Table 5. Costs include all-distance transmission, pipelines, and distribution, but they exclude externalities.

b) Same as (a), but for a 2050 BAU case (Supplemental Information) and 2050 LCOEs for each generator from Table 5.

c) The 2050 LCOE of WWS in the state combines the 2050 distribution of WWS generators from Table 3 with the 2050 mean LCOEs for each WWS generator from Table 5. The LCOE accounts for all-distance transmission and distribution and storage (footnotes to Tables 2 and 5).
d) The total cost of electricity use in the electricity sector in the BAU (the product of electricity use and the LCOE) less the total cost in the electricity sector in the WWS scenario and less the annualized cost of the assumed efficiency improvements in the electricity sector in the WWS scenario. (See SI and Delucchi et al., 2015, for details.)
e) Total cost of air pollution per year in the state from Table 7 divided by the 2050 population of the state.
f) Total climate cost per year in the state due to U.S. emissions (Table 8) divided by the 2050 population of the state.
g) Total climate cost per year to the world due to state's emissions (Table 8) divided by the 2050 population of the state.
h) The sum of columns (d), (e), and (g).

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 it will eliminate energy-related climate change costs to the world while causing variable climate impacts on individual states. This section discusses these topics.

8.A. Air Pollution Cost Reductions due to WWS

The benefits of reducing air pollution mortality and its costs in each U.S. state can be quantified with a top-down approach and a bottom-up approach.

The top-down approach. 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 is 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. premature mortality rate due to ozone and particulate matter is 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 premature mortalities per year due to all anthropogenic air pollution in the U.S. in 1990, when air pollution levels were higher than today.

Bottom-up approach. 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 7 shows the resulting estimates of premature mortality for each state in the U.S. due to the sum of $PM_{2.5}$ and O_3, as calculated with 2010-2012 air quality data. The mean values for the U.S. for $PM_{2.5}$ are ~48,000 premature mortalities/yr, with a range of 12,000-95,000/yr and for O_3 are ~14,000 premature mortalities/yr, with a range of 7,000-21,000/yr. Thus, overall, the bottom-up approach gives ~62,000 (19,000-115,000) premature mortalities/year for $PM_{2.5}$ plus O_3. The top-down estimate (50,000–100,000), from Jacobson (2010), is within the bottom-up range.

Table 7. Avoided air pollution $PM_{2.5}$ plus O_3 premature mortalities by state in 2010-2012 and 2050 and mean avoided costs (in 2013 dollars) from mortalities and morbidities in 2050.

State	2012 Population	2010-2012 Low avoided mortalities/yr	2010-2012 Mean avoided mortalities/yr	2010-2012 High avoided mortalities/yr	2050 Mean avoided mortalities/yr	2050 Mean avoided cost ($mil./yr)
Alabama	4,822,023	291	954	1,784	596	7,799
Alaska	731,449	23	84	155	71	922
Arizona	6,553,255	517	1,518	2,729	1,911	24,988
Arkansas	2,949,131	126	448	859	301	3,937
California	38,041,430	3,825	12,528	23,194	9,778	127,868
Colorado	5,187,582	262	699	1,215	568	7,428
Connecticut	3,590,347	235	729	1,338	393	5,142
Delaware	917,092	61	198	367	132	1,723
Florida	19,317,568	818	2,681	5,018	3,118	40,770
Georgia	9,919,945	632	2,043	3,799	1,585	20,733
Hawaii	1,392,313	51	192	374	121	1,584
Idaho	1,595,728	73	219	395	185	2,420
Illinois	12,875,255	942	3,150	5,909	1,811	23,678
Indiana	6,537,334	523	1,704	3,170	1,037	13,562
Iowa	3,074,186	164	540	1,010	272	3,552
Kansas	2,885,905	121	377	695	220	2,878
Kentucky	4,380,415	280	887	1,638	542	7,089
Louisiana	4,601,893	236	780	1,462	465	6,075
Maine	1,329,192	43	136	250	71	927
Maryland	5,884,563	436	1,350	2,475	966	12,630
Massachusetts	6,646,144	328	1,033	1,906	628	8,206
Michigan	9,883,360	565	1,744	3,192	927	12,129
Minnesota	5,379,139	205	692	1,305	475	6,213
Mississippi	2,984,926	167	553	1,036	320	4,186
Missouri	6,021,988	361	1,123	2,065	700	9,156
Montana	1,005,141	37	139	266	81	1,054
Nebraska	1,855,525	74	245	460	142	1,863
Nevada	2,758,931	212	567	986	632	8,261
New Hampshire	1,320,718	54	171	317	119	1,557
New Jersey	8,864,590	467	1,528	2,854	946	12,373
New Mexico	2,085,538	117	353	640	184	2,409
New York	19,570,261	901	3,137	5,963	1,708	22,342
North Carolina	9,752,073	543	1,672	3,065	1,485	19,417
North Dakota	699,628	18	57	105	29	385
Ohio	11,544,225	911	2,920	5,403	1,551	20,279
Oklahoma	3,814,820	186	606	1,131	412	5,383
Oregon	3,899,353	132	453	849	403	5,265
Pennsylvania	12,763,536	921	3,065	5,730	1,649	21,563
Rhode Island	1,050,292	53	166	307	87	1,131
South Carolina	4,723,723	288	948	1,774	663	8,667
South Dakota	833,354	26	81	150	45	595
Tennessee	6,456,243	432	1,380	2,558	1,047	13,688
Texas	26,059,203	1,294	4,217	7,869	4,142	54,161
Utah	2,855,287	209	598	1,060	598	7,821

Vermont	626,011	20	62	115	36	473
Virginia	8,185,867	436	1,352	2,483	1,051	13,740
Washington	6,897,012	242	839	1,592	832	10,887
West Virginia	1,855,413	101	327	610	147	1,920
Wisconsin	5,726,398	294	934	1,727	544	7,109
Wyoming	576,412	23	62	108	32	417
United States	313,281,717	19,273	62,241	115,461	45,754	598,356

Premature mortality due to ozone exposure is 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 are as in Jacobson (2010). The low ambient concentration threshold for ozone premature mortality is assumed to be 35 ppbv (Jacobson, 2010 and reference therein). Mortality due to $PM_{2.5}$ exposure is 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) are applied to all ages as in Lepeule et al. (2012) rather than to those over 30 years old as in Pope et al. (2002). The threshold for $PM_{2.5}$ is zero but concentrations below 8 $\mu g/m^3$ are down-weighted as in Jacobson (2010). For each county in each state, mortality rates are 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 are 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 are not available for 25% of the population and for the ozone calculations data are not available for 26% of the population. For these populations, mortality rates are set equal to the minimum county value for a given state, as determined per the method specified above. In cases where 2012 data are unavailable, data from 2013 are 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 are 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 are not available (and the minimum county mortality rate within the state is used in these cases, as specified above). 2050 estimates of avoided mortality are derived from 2010-2012 estimates as detailed in the Supplemental Information. The cost of avoided mortalities plus associated morbidities is determined as described in the text.

Mortality and Non-mortality costs of air pollution. The total damage cost of air pollution from fossil fuel and biofuel combustion and evaporative emissions is the sum of mortality costs, morbidity costs, and non-health costs such as lost visibility and agricultural output. We estimate this total damage cost of air pollution in each state S in a target year Y as the product of an estimate of the number of premature deaths due to air pollution and the total cost of air pollution per death. The total cost of air pollution premature death is equal to the value of a statistical life multiplied by the ratio of the value of total mortality-plus-non-mortality impacts to mortality impacts. The number of premature deaths in the base year is as described in the footnote to Table 7. The number of deaths in 2050 is estimated by scaling the base-year number by factors that account for changes in population, exposure, and air pollution. The method is fully documented in the Supplemental Information and Delucchi et al. (2015).

Given this information, the total social cost due to air pollution mortality, morbidity, lost productivity, and visibility degradation in the U.S. in 2050 is conservatively estimated from the ~45,800 (11,600-104,000) premature mortalities/yr to be \$600 (85-2,400) bil./yr using \$13.1 (7.3-23.0) million/mortality in 2050. Eliminating these costs in 2050 represents a savings equivalent to ~3.6 (0.5-14.3) % of the 2014 U.S. gross domestic product of \$16.8 trillion. The U.S.-averaged payback time of the cost of installing all WWS generators in Table 2 due to the avoided air pollution costs alone is 20 (5-140) years.

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

This section provides estimates of two kinds of climate change costs due to greenhouse gas (GHG) emissions from energy use (Table 8). GHG emissions are defined here to include emissions of carbon dioxide, other greenhouse gases, and air pollution particles that cause global warming, converted to equivalent carbon dioxide. A 100% WWS system in each state would eliminate such damages. The two kinds of costs calculated are

1) The cost of climate change impacts to the world and U.S. *attributable to* emissions of GHGs from each of the 50 states, and

2) The cost of climate-change impacts *borne* by each state due to U.S. GHG emissions.

Costs due to climate change include coastal flood and real estate damage costs, energy-sector costs, health costs due to heat stress and heat stroke, influenza and malaria costs, famine costs, ocean acidification costs, increased drought and wildfire costs, severe weather costs, and increased air pollution health costs. These costs are partly offset by fewer extreme cold events and associated reductions in illnesses and mortalities and gains in agriculture in some regions. Net costs due to global-warming-relevant emissions are embodied in the social cost of carbon dioxide. The range of the 2050 social cost of carbon from recent papers is \$500 (282-1,063)/metric tonne-CO_2e in 2013 dollars (Supplemental Information). This range is used to derive the costs in Table 8. State costs due to their own air pollution also take into account a study of the state-by-state damage versus benefits of climate change (Supplemental Information).

Table 8. Percent of 2010 world CO_2 emissions by state (EIA, 2011), mean estimate of avoided (+) or increased (-1) 2050 climate change cost in each state due to converting the U.S. as a whole to 100% WWS for all purposes, and low, medium, and high estimates of avoided 2050 global climate-change costs due to converting to 100% WWS for all purposes in each state individually. All costs are in 2013 dollars.

	2010	2050	2050 avoided global climate cost (\$2013 bil./yr)		
State	Percent of world CO_2 emissions	Medium avoided state climate costs (\$2013 bil./yr)	Low	Medium	High
Alabama	0.39	9.63	170.6	80.1	45.2
Alaska	0.12	-1.09	57.0	26.8	15.1
Arizona	0.28	12.92	122.5	57.6	32.4
Arkansas	0.20	5.51	95.2	44.7	25.2
California	1.04	25.24	514.4	241.7	136.2
Colorado	0.28	-1.19	121.8	57.2	32.3
Connecticut	0.10	-0.75	39.8	18.7	10.5
Delaware	0.04	0.89	15.6	7.3	4.1
Florida	0.68	70.63	299.0	140.5	79.2
Georgia	0.46	13.82	202.6	95.2	53.7
Hawaii	0.06	3.35	28.7	13.5	7.6
Idaho	0.05	-0.80	20.7	9.7	5.5
Illinois	0.68	0.24	274.1	128.8	72.6
Indiana	0.62	0.91	251.9	118.3	66.7
Iowa	0.25	-2.53	101.6	47.7	26.9
Kansas	0.22	3.38	89.0	41.8	23.6
Kentucky	0.45	4.37	195.7	91.9	51.8
Louisiana	0.67	14.68	317.8	149.3	84.2

Maine	0.05	-2.15	21.4	10.1	5.7
Maryland	0.19	4.07	84.0	39.5	22.2
Massachusetts	0.20	-3.29	79.0	37.1	20.9
Michigan	0.47	-4.44	191.5	89.9	50.7
Minnesota	0.28	-1.93	110.9	52.1	29.4
Mississippi	0.18	6.09	79.6	37.4	21.1
Missouri	0.40	7.91	161.6	75.9	42.8
Montana	0.10	-0.58	42.3	19.9	11.2
Nebraska	0.16	-2.62	62.9	29.5	16.7
Nevada	0.10	2.99	44.4	20.9	11.8
New Hampshire	0.05	-1.42	19.3	9.0	5.1
New Jersey	0.33	6.57	127.8	60.0	33.8
New Mexico	0.17	1.02	75.5	35.4	20.0
New York	0.48	2.15	183.5	86.2	48.6
North Carolina	0.37	10.89	161.7	76.0	42.8
North Dakota	0.16	0.31	65.2	30.6	17.3
Ohio	0.70	0.61	284.0	133.4	75.2
Oklahoma	0.32	8.06	152.9	71.8	40.5
Oregon	0.11	-4.24	53.9	25.3	14.3
Pennsylvania	0.74	0.35	283.8	133.3	75.2
Rhode Island	0.03	-0.76	12.8	6.0	3.4
South Carolina	0.23	8.95	102.5	48.1	27.1
South Dakota	0.04	-0.54	17.6	8.2	4.6
Tennessee	0.31	9.46	136.3	64.0	36.1
Texas	1.98	62.26	935.0	439.3	247.6
Utah	0.19	0.45	85.3	40.1	22.6
Vermont	0.02	-0.91	6.8	3.2	1.8
Virginia	0.29	7.40	128.2	60.2	34.0
Washington	0.21	-7.28	102.4	48.1	27.1
West Virginia	0.29	0.26	126.4	59.4	33.5
Wisconsin	0.29	-3.26	117.1	55.0	31.0
Wyoming	0.19	-0.32	85.1	40.0	22.5
United States	16.2	265.3	7,058.7	3,316.1	1,869.4

Table 8 indicates that, in some, primarily northern cold states, climate change due to total U.S. emissions may contribute to fewer extreme cold events and improved agriculture; however, the sum of all states' emissions cause a net positive damage to the U.S. as a whole (with total damage caused by all states' emissions in 2050 of $265 bil./yr in 2013 dollars) and to the world (with total damage to the world caused by all states' emissions of $3.3 (1.9-7.1) tril./yr). Thus, the global climate cost savings per person in the U.S. due to reducing all U.S. climate-relevant emissions through a 100% WWS system is ~$8,300 (4,700-17,600)/person/yr (in 2013 dollars) (Table 6).

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 because of the additional complexity required and greater uncertainty as to where those jobs will be located.

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 are run assuming that the WWS electricity sector is fully developed by 2050. Existing capacities are 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). This analysis assumes that each year from 2010 to 2050 1/40th of the WWS infrastructure is built.

Table 9. Estimated 40-year construction jobs, 40-year operation jobs, construction plus operation jobs minus jobs lost, annual earnings corresponding to construction and operation jobs produced, and net earnings from construction plus operation jobs produced minus jobs lost, by state, due to converting to WWS. Earnings are in 2013 dollars per year.

State	40-year construction jobs	40-year operation jobs	Job losses in current energy industry	40-year net construction plus operation jobs created minus jobs lost	Earnings from new 40-year construction jobs ($bil 2013/yr)	Earnings from new 40-year operation jobs ($bil 2013/yr)	Net earnings from new construction plus operation jobs minus jobs lost ($bil 2013/yr)
Alabama	130,925	49,650	57,095	123,480	7.28	3.11	6.40
Alaska	14,662	15,099	24,423	5,339	0.87	1.10	0.26
Arizona	49,200	18,536	63,825	3,911	2.92	1.23	-0.31
Arkansas	53,887	20,481	38,570	35,798	3.04	1.36	1.70
California	315,982	142,153	413,097	45,039	18.12	9.51	-1.26
Colorado	49,417	21,119	76,576	-6,040	2.89	1.48	-0.98
Connecticut	40,487	21,662	34,194	27,955	2.25	1.40	1.27
Delaware	8,286	6,458	8,922	5,822	0.48	0.43	0.28
Florida	222,082	90,727	173,635	139,175	12.41	5.76	6.03
Georgia	146,597	73,419	95,086	124,929	8.24	4.74	6.33
Hawaii	8,239	4,239	13,599	-1,120	0.47	0.29	-0.19
Idaho	16,877	6,707	14,746	8,837	0.97	0.47	0.40
Illinois	132,687	59,709	138,722	53,675	7.46	4.16	1.93
Indiana	119,791	47,951	71,464	96,277	6.64	3.26	4.90
Iowa	57,914	25,106	29,899	53,121	3.25	1.76	2.92
Kansas	29,065	13,346	42,836	-425	1.70	0.96	-0.34
Kentucky	142,163	47,719	62,687	127,195	7.78	2.95	6.35
Louisiana	174,500	143,400	134,860	183,040	10.18	9.51	10.26
Maine	17,771	13,381	12,446	18,706	1.02	0.92	1.07
Maryland	51,557	35,893	54,286	33,164	2.94	2.38	1.52
Massachusetts	53,490	37,950	64,380	27,060	3.05	2.55	1.10
Michigan	89,250	58,810	99,191	48,869	5.12	4.10	2.28
Minnesota	46,025	29,767	56,345	19,447	2.67	2.14	0.87

Mississippi	100,778	40,659	39,126	102,310	5.54	2.56	5.37
Missouri	60,791	23,469	59,914	24,345	3.41	1.60	0.82
Montana	13,833	5,642	16,202	3,273	0.79	0.39	0.05
Nebraska	26,533	12,006	23,343	15,196	1.54	0.85	0.75
Nevada	27,457	9,140	27,589	9,008	1.56	0.60	0.24
New Hampshire	10,402	5,697	13,662	2,437	0.58	0.39	0.02
New Jersey	86,049	58,606	90,836	53,819	4.88	3.90	2.43
New Mexico	20,885	9,663	41,674	-11,126	1.23	0.70	-0.98
New York	174,775	94,644	187,203	82,216	9.75	6.19	2.85
North Carolina	99,676	63,199	94,223	68,652	5.70	4.16	3.28
North Dakota	21,744	8,574	26,690	3,628	1.21	0.57	-0.08
Ohio	151,668	66,117	123,109	94,677	8.47	4.46	4.32
Oklahoma	46,516	20,350	95,445	-28,579	2.69	1.43	-2.55
Oregon	21,564	14,235	36,020	-221	1.26	1.00	-0.26
Pennsylvania	279,540	107,584	158,788	228,337	15.24	6.83	10.97
Rhode Island	7,473	5,775	9,892	3,356	0.43	0.39	0.12
South Carolina	58,473	40,345	48,132	50,687	3.37	2.67	2.68
South Dakota	10,244	4,714	8,028	6,930	0.60	0.33	0.37
Tennessee	148,143	49,950	63,345	134,748	8.14	3.09	6.80
Texas	312,979	191,331	571,429	-67,119	18.73	13.52	-7.71
Utah	29,857	11,987	37,942	3,902	1.72	0.82	-0.11
Vermont	2,496	1,005	6,455	-2,953	0.14	0.07	-0.24
Virginia	89,362	57,779	83,707	63,434	5.14	3.83	3.11
Washington	38,226	24,927	67,603	-4,449	2.17	1.75	-0.81
West Virginia	53,944	20,295	53,862	20,377	2.95	1.30	0.49
Wisconsin	51,458	33,200	54,168	30,490	2.96	2.32	1.50
Wyoming	15,806	7,731	40,009	-16,472	0.92	0.56	-1.32
United States	3,931,527	1,971,907	3,859,275	2,044,158	222.9	131.9	85

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 a compilation 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 9 suggests that the JEDI models estimate the number of 40-year operation jobs as 2.0 million across the U.S. due to WWS. This estimate falls within the range of 0.9-4.8 million jobs derived from the aggregation of models shown in Table 10.

Table 10. Estimated number of permanent operations, maintenance, and fuel processing jobs per installed MW of proposed new energy technology plants (Table 2).

		Jobs per installed MW		Number of permanent jobs	
Energy Technology	Installed MW	Low	High	Low	High
Onshore wind	1,639,819	0.14	0.40	229,575	655,927
Offshore wind	780,921	0.14	0.40	109,329	312,368
Wave device	27,036	0.14	0.40	3,785	10,814
Geothermal plant	20,845	1.67	1.78	34,811	37,103
Hydroelectric plant	3,789	1.14	1.14	4,319	4,319
Tidal turbine	8,823	0.14	0.40	1,235	3,529
Residential roof PV	375,963	0.12	1.00	45,116	375,963

Com/gov roof PV	274,733	0.12	1.00	32,968	274,733
Solar PV plant	2,323,800	0.12	1.00	278,856	2,323,800
CSP plant	363,640	0.22	1.00	80,001	363,640
Solar thermal	469,008	0.12	1.00	56,281	469,008
Total	6,288,375			876,275	4,831,206

9.B. Job Loss Analysis

Table 11 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 11. 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	58,870[f]
Coal and oil transportation	2,448,300[g]
Other	171,500[h]
Less petroleum jobs retained	-50,000[i]
Total	**3,859,000**

[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 11). Nationally, the non-fuel output from oil refineries is ~10% of refinery output (EIA, 2013). 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. This study does not address the economics of the remaining petroleum industry.

In sum, the shift to WWS may result in the displacement of ~3.86 million jobs in current fossil- and nuclear-related industries in the U.S. At $69,930/yr per job – close to the average for the WWS jobs – the corresponding loss in revenues is ~$270 billion.

9.C. Jobs Analysis Summary

The JEDI models predict the creation of ~3.9 million 40-year construction jobs and ~2.0 million 40-year operation and maintenance jobs for the WWS generators proposed. The shift to WWS will simultaneously result in the loss of ~3.9 million in the current fossil-based electricity generation, petroleum refining, and uranium production industries in the U.S. Thus, a net of ~2.0 million 40-year jobs will be created in the U.S. The direct and indirect earnings from WWS amount to $223 bil./year during the construction stage and $132 bil./yr for operation. The annual earnings lost from fossil-fuel industries total ~$270 bil./yr giving a net gain in annual earnings of ~$85 bil./yr.

10. Energy Efficiency

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 up to 30% (McKinsey and Co., 2009; Siddiqui, 2009; Farese, 2012; Kavalec et al., 2012; CEC, 2012).

11. Timeline for Implementing the Roadmaps

Figure 5 shows a proposed timeline for the implementation of the roadmaps presented here. The plans call for 80-85% conversion to WWS by 2030 and 100% by 2050. For such a transition to occur, conversions need to occur rapidly for technologies as follows:

Power plants: by 2020, no more construction of new coal, nuclear, natural gas, or biomass fired power plants; all new power plants built are WWS. This is feasible because few power plants are built every year, and most relevant WWS electric power generator technologies are already cost competitive. We do not believe a technical or economic barrier exists to ramping up production of WWS technologies, as history suggests that rapid ramp-ups of production can occur given strong enough political will. For example during World War II, aircraft production increased from nearly zero to 330,000 over five years.

Heating, drying, and cooking in the residential and commercial sectors: by 2020, all new devices and machines are powered by electricity. This is feasible because the electric versions of all of these products are already available, and all sectors can use electricity without any adaptation (the devices can just be plugged in).

Large-scale waterborne freight transport: by 2020-2025, all new ships are electrified and/or use electrolytic hydrogen, all new port operations are electrified, and port retro-electrification is well underway. This should be feasible for relatively large ships and ports because large ports are centralized and few ships are built each year. Policies may be needed to incentivize the early retirement of ships that do not naturally retire before 2050.

Rail and bus transport: by 2025, all new trains and buses are electrified. This will take a bit longer because we need also to make changes to the supporting energy-delivery infrastructure, and these are somewhat decentralized across the U.S. However, relatively few producers of buses and trains exist, and the supporting energy infrastructure is concentrated in major cities.

Off-road transport, small-scale marine: by 2025 to 2030, all new production is electrified. If these vehicles can all be battery powered, conversion will be simplified because electricity is everywhere. The potential slowdown in converting these sectors may be social.

Heavy-duty truck transport: by 2025 to 2030, all new vehicles are electrified or use electrolytic hydrogen. It may take 10-15 years for manufacturers to completely retool and for enough of the supporting energy-delivery infrastructure to be in place.

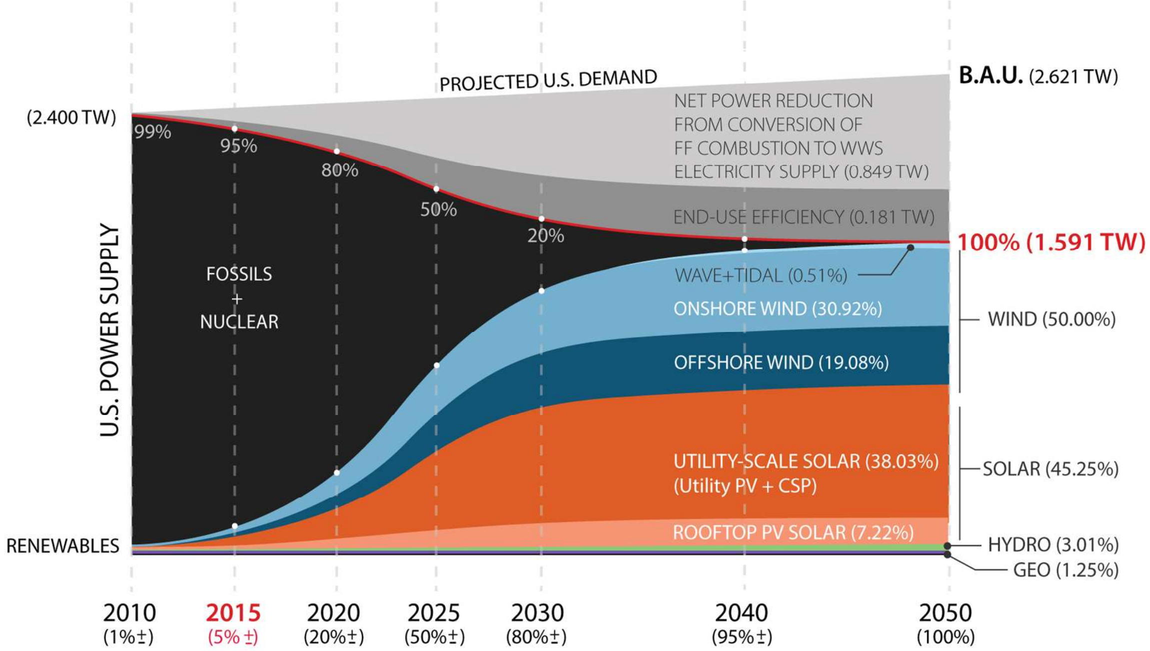
Light-duty on-road transport: by 2025-2030, all new vehicles are electrified. It takes time for manufacturers to retool, but more importantly, it will take several years to get the energy-delivery infrastructure in place, because it will need to be everywhere by 2030 when no more ICEV are made.

Short-haul aircraft: by 2035, all new small, short-range planes are battery- or electrolytic-hydrogen powered. Changing the design and manufacture of airplanes and the design and operation of airports are the main limiting factors to a more rapid transition.

Long-haul aircraft: by 2040, all remaining new aircraft are electrolytic cryogenic hydrogen (Jacobson and Delucchi, 2011, Section A.2.7) with electricity power for idling, taxiing, and internal power. The limiting factors to a faster transition are the time and social changes required for the redesign of aircraft and the design and operation of airports.

During the transition, conventional fuels will be needed along with existing WWS technologies to produce the remaining WWS infrastructure. The use of such fuels results in lifecycle carbon emissions that vary, depending on where the technologies are manufactured (e.g., Yue et al., 2014). However, at least some of that conventional energy would be used in any case to produce conventional power plants and automobiles, for example, if the plans proposed here were not implemented. In fact, it is not known whether the total lifecycle energy required to manufacture the main components of the WWS energy system, mainly solar panels and wind turbines, will be much different from the total lifecycle energy required to manufacture *all* of the components of the conventional BAU energy system, which includes power plants, refineries, mining equipment, oil and gas wells, pipelines, tanker ships, trucks, rail cars, and more. In any event, as the fraction of WWS energy increases, conventional energy generation decreases, ultimately to zero, at which point all new WWS devices are produced by existing WWS devices with zero emissions. In sum, the creation of WWS infrastructure *might* result in a temporary, minor increase in emissions before emissions are ultimately reduced to zero, and might have minor impacts on energy use in the industrial sector.

Figure 5. Time-dependent change in U.S. end-use power demand for all purposes (electricity, transportation, heating/cooling, and industry) and its supply by conventional fuels and WWS generators based on the 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 on the horizontal date axis are the percent conversion to WWS that has occurred by that year. 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.



12. Recommended First Steps

This section discusses short-term policy options to aid conversion to WWS at the state level. Within each section, the policy options listed are listed roughly in order of proposed priority.

12.1. Energy Efficiency Measures

- Expand Renewable Energy Standards and Energy Efficiency Resource Standards.

- Incentivize 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.

- 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; improved wall, floor, ceiling, and pipe insulation; 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.

- Revise building codes as new technologies become 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.

- Introduce a Public Benefit Funds (PBF) program for energy efficiency. Fund the program 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.

12.2. Energy Supply Measures

- Increase Renewable Portfolio Standards (RPS).

- Extend or create state WWS production tax credits.

- Implement taxes on emissions by current utilities to encourage their phaseout.

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

- Incentivize clean-energy backup emergency power systems rather than diesel/gasoline generators at both the household and community levels.

- Incentivize home or community energy storage (through battery systems) accompanying rooftop solar to mitigate problems associated with grid power losses.

12.3. Utility Planning and Incentive Structures

- Incentive the development of utility-scale grid storage.

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

- Implement virtual net metering (VNM) for small-scale energy systems. VNM allows a utility customer to assign the net production from an electrical generator (e.g., solar PV) on his or her property to another metered account 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, useful policies would be to (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, and (3) remove the barrier to inter-load zone transmission of net-metered renewable power.

12.4. Transportation

- Promote more public transit by increasing its availability and providing compensation to commuters for not purchasing parking passes.

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

- Adopt legislation mandating BEVs for short- and medium distance government transportation and using incentives and rebates to encourage the transition of commercial and personal vehicles to BEVS.

- 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 incentivized as well.

- 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.

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

12.5. Industrial Processes

- Provide financial incentives for industry to convert to electricity and electrolytic hydrogen for high temperature and manufacturing processes.

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

12.6 State Planning and Incentive Structures

- Lock in in-state fossil fuel and nuclear 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.

- Work with local and regional governments to manage zoning and permitting issues within existing regional planning efforts or pre-approve sites to reduce the cost 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.

- 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.

13. Summary

This study develops consistent roadmaps for each of the 50 United States to convert their energy infrastructures for all purposes into clean and sustainable ones powered by wind, water, and sunlight (WWS) producing electricity and electrolytic hydrogen for all purposes (electricity, transportation, heating/cooling, and industry).

The study evaluates U.S. WWS resources and proposes a mix of WWS generators that can match projected 2050 demand. A separate grid integration study (Jacobson et al., 2015) quantifies the additional generators and storage needed to ensure grid reliability. The numbers of generators from that study are included here. This study also evaluates the state-by-state land and water areas required, energy, air pollution, and climate cost changes, and net jobs created from such a conversion.

The conversion from combustion to a completely electrified system for all purposes is calculated to reduce U.S.-averaged end-use load ~39.3% with ~82.4% of this due to electrification and the rest due to end-use energy efficiency improvements. Additional end-use energy efficiency measures may reduce load further. The conversion to WWS should stabilize energy prices since fuel costs will be zero.

Remaining all-purpose annually-averaged end-use U.S. load is proposed to be met (based on 2050 energy estimates) with 328,000 new onshore 5-MW wind turbines (providing 30.9% of U.S. energy for all purposes), 156,200 off-shore 5-MW wind turbines (19.1%), 46,480 50-MW new utility-scale solar-PV power plants (30.7%), 2,273 100-MW utility-scale CSP power plants (7.3%), 75.2 million 5-kW residential rooftop PV systems (3.98%), 2.75 million 100-kW commercial/government rooftop systems (3.2%), 208 100-MW geothermal plants (1.23%), 36,050 0.75-MW wave devices (0.37%), 8,800 1-MW tidal turbines (0.14%), and 3 new hydroelectric power plants (all in Alaska). The capacity of existing plants would be increased slightly so that hydro supplies 3.01% of all-purpose power. The parallel grid integration study suggests that an additional 1,364 CSP plants (providing an additional ~4.38% of annually-averaged load) and 9,380 50-MW solar-thermal collection systems for heat storage in soil (providing an additional 7.21% of annually-averaged load) are needed to ensure a reliable grid. This is just one possible mix of generators. 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).

The additional footprint on land for WWS devices is equivalent to about 0.42% 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 1.6% 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.

The 2013 business costs of hydroelectric, onshore wind, utility-scale solar, and solar thermal collectors for heat are already similar to or less than the costs of natural gas combined cycle. Rooftop PV, offshore wind, tidal, and wave are more expensive. By 2050, though, the business costs of all WWS technologies are expected to drop, most significantly for offshore wind, tidal, wave, rooftop PV, CSP, and utility PV, whereas conventional fuel costs are expected to rise.

The 50-state roadmaps are anticipated to create ~3.9 million 40-year construction jobs and ~2.0 million 40-year operation jobs for the energy facilities alone, outweighing the ~3.9 million jobs lost to give a net gain of 2.0 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 ~$223 bil./yr in 2013 dollars and annual earnings during operation of the WWS facilities are estimated at ~$132 bil./year. Net earnings from construction plus operation minus lost earnings from lost jobs are estimated at ~$85 bil./yr.

The state roadmaps will reduce U.S. air pollution mortality by ~62,000 (19,000-115,000) U.S. air pollution premature mortalities/yr today and ~46,000 (12,000-104,000) in 2050, avoiding ~$600 ($85-$2,400) bil./year (2013 dollars) in 2050, equivalent to ~3.6 (0.5-14.3) percent of the 2014 U.S. gross domestic product.

Converting would further eliminate ~$3.3 (1.9-7.1) tril./yr in 2050 global warming costs to the world due to U.S. emissions. These plans will result in the average person in the U.S. in 2050 saving $260 (190-320)/yr in energy costs ($2013 dollars), $1,500 (210-6,000)/yr in health costs, and $8,300 (4,700-17,600)/yr in climate costs.

Many uncertainties in the analysis here are captured in broad ranges of energy, health, and climate costs given. However, these ranges may miss costs due to limits on supplies caused by wars or political/social opposition to the roadmaps. As such, the estimates should be reviewed periodically.

The timeline for conversion is proposed as follows: 80-85% of all energy to be WWS by 2030 and 100% by 2050. If this timeline is followed, implementation of these plans and similar ones for other countries worldwide will eliminate energy-related global warming; air, soil, and water pollution; and energy insecurity.

Based on the scientific results presented, current barriers to implementing the roadmaps are neither technical nor economic. As such, they must be social and political. Such barriers are due partly to the fact that most people are unaware of what changes are possible and how they will benefit from them and partly to the fact that many with a financial interest in the current energy industry resist change. However, because the benefits of converting (reduced global warming and air pollution; new jobs and stable energy prices) far exceed the costs, converting has little downside. This study elucidates the net benefits and quantifies what is possible thus should reduce social and political barriers to implementing the roadmaps.

Acknowledgments

We would like to thank Michael J. Dvorak, Elaine Hart, Anthony R. Ingraffea, Robert W. Howarth, Jannette M. Barth, Karl Burkart, Jon Wank, Mark Ruffalo, and Marco Krapels for helpful comments and insight and The Solutions Project for partial student funding. The spreadsheets and links to infographics for this paper can be found in Delucchi et al. (2015).

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This paper presents a consistent set of roadmaps for converting the energy infrastructures of each of the 50 United States to 100% wind, water, and sunlight (WWS) for all purposes (electricity, transportation, heating/cooling, and industry) by 2050. Such conversions are obtained by first projecting conventional power demand to 2050 in each sector then electrifying the sector, assuming the use of some electrolytic hydrogen in transportation and industry and applying modest end-use energy efficiency improvements. Such state conversions may reduce conventional 2050 U.S.-averaged power demand by ~39%, with most reductions due to the efficiency of electricity over combustion and the rest due to modest end-use energy efficiency improvements. The conversions are found to be technically and economically feasible with little downside. They nearly eliminate energy-related U.S. air pollution and climate-relevant emissions and their resulting health and environmental costs while creating jobs, stabilizing energy prices, and minimizing land requirements. These benefits had not previously been quantified for the 50 states. Their elucidation may reduce the social and political barriers to implementing clean-energy policies for replacing conventional combustible and nuclear fuels. Several such policies are proposed herein for each energy sector.