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100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States†

Mark Z. Jacobson,*[a] Mark A. Delucchi,[b] Guillaume Bazouin,[a] Zack A. F. Bauer,[a] Christa C. Heavey,[a] Emma Fisher,[a] Sean B. Morris,[a] Diniana J. Y. Piekutowski,[a] Taylor A. Vencill[a] and Tim W. Yeskoo[a]

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 per year today and ∼46 000 (12 000–104 000) in 2050, avoiding ∼$600 ($85–$2400) bil. per 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. per year 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) per year in energy costs ($2013 dollars) and U.S. health and global climate costs per person decreasing by ∼$1500 (210–6000) per year and ∼$8300 (4700–17 600) per year, 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.

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Broader context

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 have 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.

1. Introduction

This paper presents a consistent set of roadmaps to convert each of the 50 U.S. states' all-purpose (electricity, transportation,

[a] *Atmosphere/Energy Program, Dept. of Civil and Env. Engineering, Stanford University, USA. E-mail: jacobson@stanford.edu; Fax: +1-650-723-7058; Tel: +1-650-723-6836*
[b] *Institute of Transportation Studies, U.C. Berkeley, USA*

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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,[1] 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[2] 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,[3] California,[4] and the world as a whole.[5–7] 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.[8]

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 will be heated 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, as previously discussed.[3,6] 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 $\sim$20% efficient, the same land used for PV produces $\sim$20 times more energy than does using the land for biofuels.

This study first 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 ref. 2. 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 roughly estimate the additional cost of transmission lines needed for this hourly balancing. Note that if we relax our assumption that each state's capacity match its annual demand, and instead allow states with especially good solar or wind resources to have enough capacity to supply larger regions, then the average levelized cost of electricity will 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 (with zero fossil fuels, biofuels, or nuclear fuels). The table is derived from a spreadsheet analysis of annually averaged end-use load data.[9] 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).

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. 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 additional 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.[6] 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.[6,10] 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.

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 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

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[a]

State	Scenario	2050 total end-use load (GW)	Residential % of total	Commercial % of total	Industrial % of total	Transport % 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	−8.8
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

Table 1 (*continued*)

State	Scenario	2050 total end-use load (GW)	Residential % of total	Commercial % of total	Industrial % of total	Transport % of total	% change in end-use power with WWS Overall	% change in end-use power with WWS Effic. only
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

[a] 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 ESI and ref. 9 for details.

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 and 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 separate grid integration study[2] 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.

Fig. 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 this requires ∼1.6% of U.S. land. The footprint associated with this spacing is trivial,

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 ref. 2. The numbers account for short- and moderate-distance transmission, distribution, forced and unforced maintenance, and array losses. Ref. 9 derives individual tables for each state

Energy technology	Rated power one plant or device (MW)	Percent of 2050 all-purpose load met by plant/device[a]	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.	Percent of U.S. land area for footprint of new plants/devices[b]	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	8823	0.00	8823	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	2273	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	1364	0.07388	0.0000
Solar thermal[e]	50	7.21	469 000	0.00	9380	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 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, maintenance-time, and array losses. The capacity factor is determined for each device in each state in ref. 9. The state-by-state capacity factors for onshore wind turbines in 2050, accounting for transmission, distribution, maintenance-time, and array losses, are calculated from actual 2013 state installed capacity[11] and power output[12] 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^{-1} or higher,[13] which corresponds to a capacity factor before transmission, distribution, maintenance, and array losses of $\sim$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%.[2] 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 ref. 9. 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 ref. 9. 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 ref. 9 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 ref. 9. [e] The installed capacities for peaking power/storage are derived in the separate grid integration study.[2] 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 ref. 2. [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*.

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.

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

Fig. 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 4 × 7 rotor diameters are used for onshore turbines and 5 × 10 diameters for offshore turbines.

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	Geothermal	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

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 (Fig. 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). Fig. 2 suggests that much more land and ocean areas with these respective capacity factors or higher are available than are needed for the roadmaps.

5.2. Solar

World solar power resources are known to be large.[16] Here, such resources are estimated (Fig. 3) for the U.S. using a 3-D climate

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 ref. 9 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 (MW$_{dc\text{-}peak}$)	Proposed installed capacity in 2050 (MW$_{dc\text{-}peak}$)	Percent of potential capacity installed	Rooftop area suitable for PVs in 2012 (km^2)	Potential capacity of suitable area in 2050 (MW$_{dc\text{-}peak}$)	Proposed installed capacity in 2050 (MW$_{dc\text{-}peak}$)	Percent of potential capacity installed
Alabama	59.7	10 130	7409	73	35.4	6150	4175	68
Alaska	7.0	760	414	54	4.2	460	242	53
Arizona	7.1	3520	1379	39	46.9	23 210	8841	38
Arkansas	36.7	7090	5217	74	27.0	5330	3720	70
California	336.1	83 150	48 412	58	220.6	55 330	31 826	58
Colorado	48.8	11 190	6684	60	40.6	9440	5706	60
Connecticut	32.2	4640	3301	71	25.1	3690	2478	67
Delaware	10.9	1940	1182	61	7.3	1320	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	3260	2291	70	7.5	1950	1320	68
Idaho	16.2	4030	2318	58	12.2	3070	1663	54
Illinois	116.3	17 220	11 537	67	110.6	16 770	10 524	63
Indiana	65.6	10 500	6652	63	54.8	8960	5354	60
Iowa	31.2	4430	3165	71	29.4	4260	2837	67
Kansas	32.1	5220	3804	73	28.1	4680	3197	68
Kentucky	52.7	8270	6076	73	32.3	5200	3575	69
Louisiana	54.2	9910	6582	66	44.6	8350	5447	65
Maine	32.2	4740	3340	70	9.4	1410	998	71
Maryland	60.5	11 550	7102	61	49.0	9530	5659	59
Massachusetts	58.6	8560	6053	71	46.4	6930	4591	66
Michigan	105.0	14 970	10 142	68	89.0	12 980	8312	64
Minnesota	52.9	9280	5564	60	54.6	9740	5985	61
Mississippi	35.5	4950	3653	74	22.6	3230	2183	68
Missouri	72.9	12 260	8270	67	58.0	9980	6396	64
Montana	11.6	1880	1391	74	8.2	1350	936	69
Nebraska	20.5	3140	2228	71	18.0	2830	1816	64
Nevada	29.4	15 120	6451	43	18.8	9600	3855	40
New Hampshire	13.9	2480	1287	52	9.3	1680	846	50
New Jersey	83.1	12 730	8345	66	60.7	9520	5917	62
New Mexico	24.7	5070	3674	72	15.7	3300	2276	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	8417	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	9768	65
Oklahoma	46.2	8150	5544	68	34.8	6270	4349	69
Oregon	43.5	8590	4431	52	21.6	4330	2185	50
Pennsylvania	136.4	18 870	13 757	73	87.9	12 410	8782	71
Rhode Island	9.9	1460	1015	70	7.8	1180	765	65
South Carolina	58.4	9220	6057	66	36.8	5950	3801	64
South Dakota	8.5	1290	857	66	8.3	1280	813	64
Tennessee	76.6	12 020	7246	60	45.9	7370	4083	55
Texas	268.9	78 190	36 792	47	216.9	63 550	27 485	43
Utah	23.1	6360	3160	50	20.9	5810	2833	49
Vermont	7.5	1110	672	61	4.5	680	402	59
Virginia	88.1	17 400	9825	56	65.8	13 190	7339	56
Washington	73.6	14 050	6774	48	37.2	7180	3141	44
West Virginia	24.3	3140	2273	72	16.1	2140	1386	65
Wisconsin	59.5	9310	6236	67	48.3	7710	4912	64
Wyoming	6.3	1050	754	72	4.5	760	430	57
United States	3197.6	660 290	379 513	57	2386	505 070	276 508	55

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 (Fig. 3).

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.)

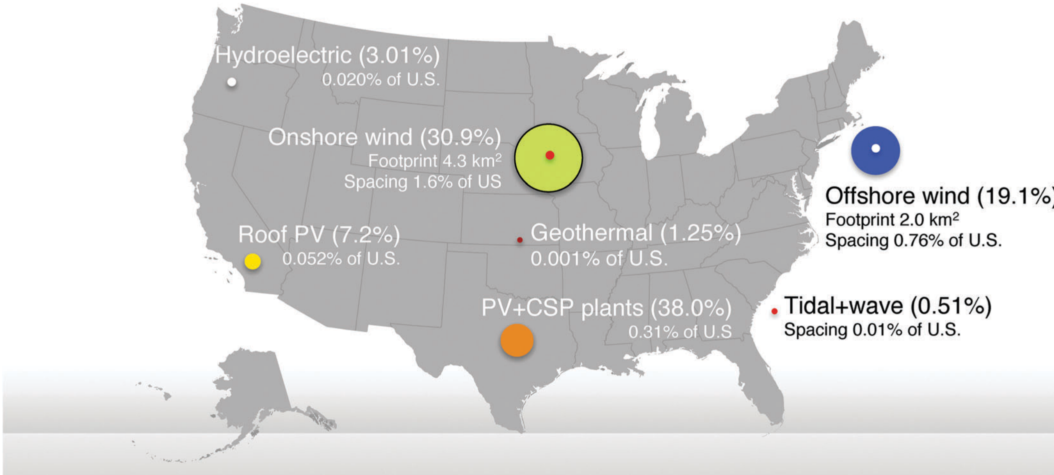

Fig. 1 Spacing and footprint areas required from Table 2 for annual power load, beyond existing 2013 resources, to repower the U.S. state-by-state for all purposes in 2050. The dots do not indicate the actual location of energy farms. For wind, the small dot in the middle is footprint on the ground or 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.

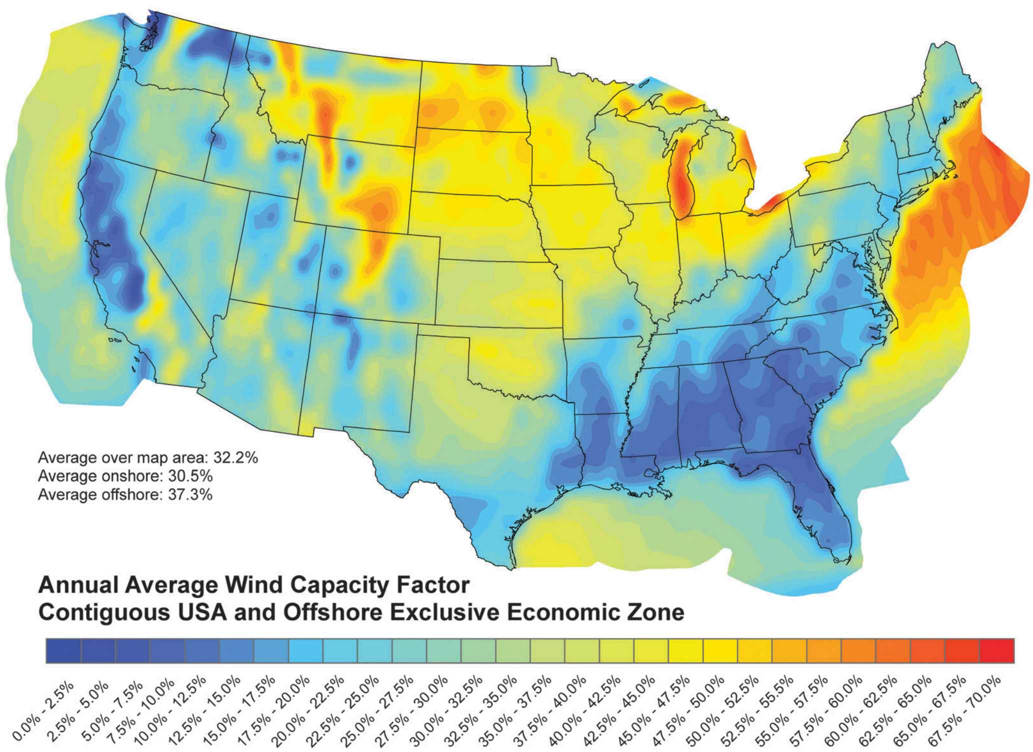

Fig. 2 Modeled 2006 annually averaged capacity factor for 5 MW REpower wind turbines (126 m diameter rotor) at 100 m hub height above the topographical surface in the contiguous United States ignoring competition among wind turbines for the same kinetic energy and before transmission, distribution, and maintenance-time losses. The model used is GATOR-GCMOM,[14,15] which is nested for one year from the global to regional scale with resolution on the regional scale of 0.6° W–E × 0.5° S–N.

Ref. 4 (Supplemental Information) and ref. 9 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

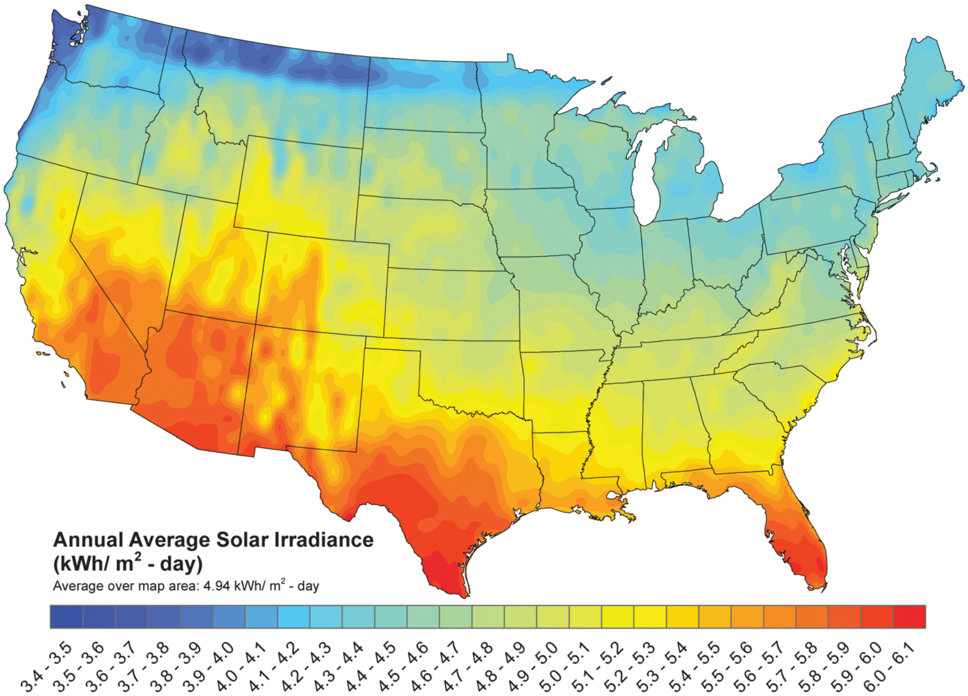

Fig. 3 Modeled 2013 annual downward direct plus diffuse solar radiation at the surface (kW h per m^2 per day) available to photovoltaics in the contiguous United States. The model used is GATOR-GCMOM,[14,15] which simulates clouds, aerosols gases, weather, radiation fields, and variations in surface albedo over time. The model is nested from the global to regional scale with resolution on the regional scale 0.6° W–E × 0.5° S–N.

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 $GW_{dc\text{-}peak}$ 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 $GW_{dc\text{-}peak}$ of installed power. The state plans here propose to cover ∼55% of installable power.

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.[17] 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.[18]

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%).[17] 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 GW h per year) of U.S. electric power, or 6.3% of the U.S. electric power supply.[19] The installed conventional hydroelectric capacity was 78.825 GW,[19] giving the capacity factor of conventional hydro as 37.7% in 2010. Fig. 4 shows the installed conventional hydroelectric by state in 2010.

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.

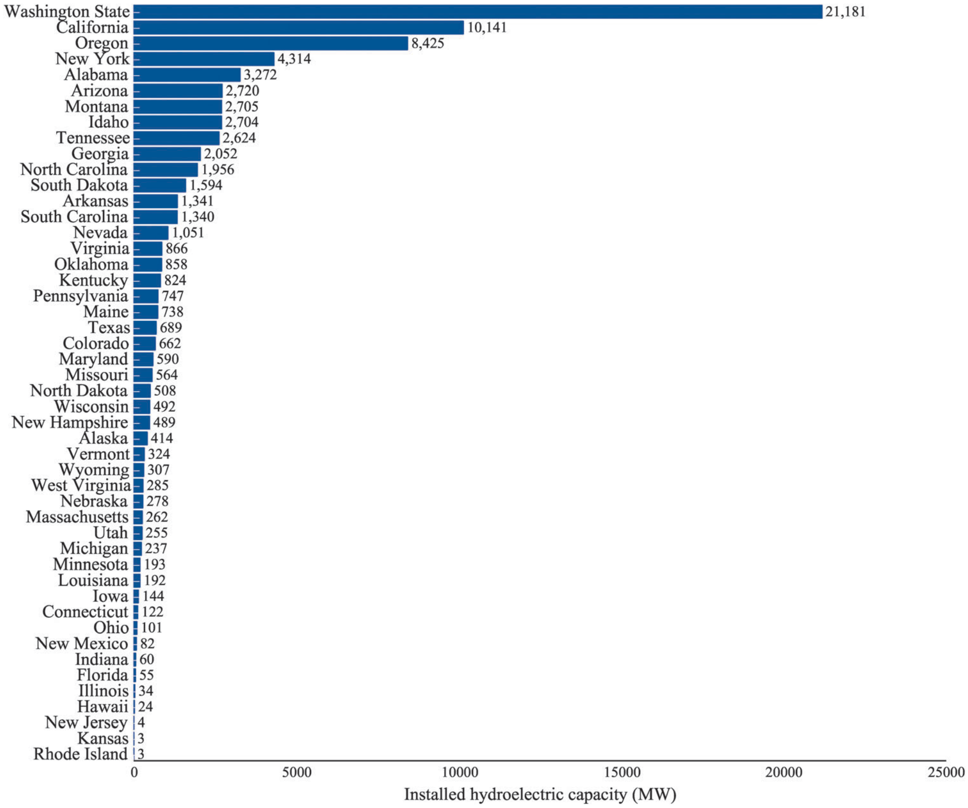

Fig. 4 Installed conventional hydroelectric by U.S. state in 2010.[19]

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 $\sim$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 2500-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, ref. 20 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, ref. 21 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 TW h per year) of delivered power from tidal streams.[22] 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 (1190 TW h) along its continental shelf edge.[23] 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

Ref. 2 develops and applies 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 can 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 curtailing; 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 ref. 2. 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[24]). 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,[25,26] few have estimated such costs in the future. The methodology used here for determining 2050 levelized costs is described in the ESI.† Table 5 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.

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) per 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 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 levelized costs of energy (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

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. $ per kWh-delivered)[a]

	Technology year 2013			Technology year 2050		
Technology	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 ($ per kWh-th)	0.057	0.070	0.064	0.051	0.074	0.063

[a] LCHB = low cost, high benefits case; HCLB = high cost, low benefits case. The methodology for determining costs is given in the ESI. 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) per kWh for standard (but not extra-long-distance) transmission for all technologies except rooftop solar PV (to which no transmission cost is assigned) and $0.0257 (0.025–0.0264) per kWh for distribution for all technologies. Transmission and distribution losses are accounted for. 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 $3600–$4000 per 3.716 m^2 collector and 0.7 kW-th per m^2 maximum power.[2]

2050 will save the average U.S. consumer $260 (190–320) per year in energy costs ($2013 dollars). In addition, WWS will save $1500 (210–6000) per year in health costs, and $8300 (4700–17 600) per year in global climate costs. The total up-front capital cost of the 2050 WWS system is ~$13.4 trillion (~$2.08 mil. per MW).

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 ref. 27, 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 per year. Similarly, from ref. 15, 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 ref. 28, 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

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 ref. 9[a]

State	(a) 2013 average LCOE conventional fuels (¢ per kWh)	(b) 2050 average LCOE conventional fuels (¢ per kWh)	(c) 2050 average LCOE of WWS (¢ per kWh)	(d) 2050 average electricity cost savings per person per year ($ per person per year)	(e) 2050 average air quality damage savings per person per year due to WWS ($ per person per year)	(f) 2050 average climate cost savings to state per person per year due to WWS ($ per person per year)	(g) 2050 average climate cost savings to world per person per year due to WWS ($ per person per year)	(h) 2050 average energy + air quality damage + world climate cost savings due to WWS ($ per person per year)
Alabama	11.4	10.7	8.7	693	1464	1808	15 046	17 203
Alaska	15.1	15.5	11.1	483	886	−1042	25 692	27 060
Arizona	11.2	10.3	8.7	250	1852	958	4266	6368
Arkansas	11.2	10.8	8.2	731	1132	1585	12 855	14 717
California	12.5	10.7	9.7	161	2503	494	4731	7395
Colorado	9.9	9.9	8.5	312	1033	−165	7957	9303
Connecticut	12.5	11.0	11.9	114	1475	−215	5359	6948
Delaware	12.0	11.1	12.8	65	2361	1218	10 045	12 470
Florida	12.7	11.6	9.1	319	1099	1905	3789	5207
Georgia	11.4	10.7	10.1	293	1568	1045	7198	9059
Hawaii	22.7	30.3	11.9	1785	1028	2176	8762	11 575
Idaho	9.4	9.0	9.0	188	1051	−349	4228	5468
Illinois	10.1	9.8	9.4	231	1790	18	9736	11 757
Indiana	10.6	10.4	9.3	436	1922	129	16 770	19 128
Iowa	9.4	9.3	8.4	392	1270	−903	17 063	18 726
Kansas	9.6	9.4	8.3	349	962	1130	13 972	15 283
Kentucky	10.1	9.6	8.7	516	1492	919	19 346	21 354
Louisiana	11.2	10.8	11.5	242	1250	3019	30 706	32 197
Maine	12.5	11.0	11.4	143	739	−1713	8029	8912
Maryland	12.0	11.1	12.5	72	1725	556	5390	7187
Massachusetts	12.5	11.0	12.7	26	1148	−460	5192	6365
Michigan	10.6	10.8	11.4	157	1280	−468	9495	10 932
Minnesota	9.4	9.3	9.8	98	963	−299	8074	9134
Mississippi	11.2	10.8	9.5	531	1357	1975	12 125	14 013
Missouri	10.1	9.8	8.5	368	1377	1190	11 418	13 162
Montana	9.4	9.0	9.0	260	1021	−564	19 245	20 526
Nebraska	9.4	9.3	8.3	382	973	−1366	15 420	16 775
Nevada	9.4	9.0	9.4	98	1628	589	4110	5836
New Hampshire	12.5	11.0	10.8	144	967	−880	5621	6732
New Jersey	12.0	11.1	12.4	57	1272	675	6174	7504
New Mexico	11.2	10.3	9.2	437	1230	523	18 095	19 762
New York	14.5	12.6	13.4	112	1168	112	4508	5789
North Carolina	11.1	10.5	11.1	131	1322	741	5170	6623
North Dakota	9.4	9.3	8.4	483	598	482	47 504	48 584
Ohio	10.6	10.4	9.6	369	1834	55	12 065	14 268
Oklahoma	10.5	10.5	8.1	655	1189	1778	15 855	17 699
Oregon	9.4	9.0	10.0	33	894	−719	4305	5232
Pennsylvania	12.0	11.1	9.8	341	1746	28	10 799	12 886
Rhode Island	12.5	11.0	12.8	48	1144	−766	6094	7286
South Carolina	11.1	10.5	11.1	193	1511	1560	8396	10 100
South Dakota	9.4	9.3	8.1	372	719	−653	9972	11 063
Tennessee	10.1	9.6	8.6	338	1620	1119	7576	9534
Texas	10.7	10.7	8.7	384	1267	1456	10 273	11 923
Utah	9.4	9.0	8.9	127	1640	93	8405	10 173
Vermont	12.5	11.0	8.7	336	726	−1392	4933	5995

Table 6 (*continued*)

State	(a) 2013 average LCOE conventional fuels (¢ per kWh)	(b) 2050 average LCOE conventional fuels (¢ per kWh)	(c) 2050 average LCOE of WWS (¢ per kWh)	(d) 2050 average electricity cost savings per person per year ($ per person per year)	(e) 2050 average air quality damage savings per person per year due to WWS ($ per person per year)	(f) 2050 average climate cost savings to state per person per year due to WWS ($ per person per year)	(g) 2050 average climate cost savings to world per person per year due to WWS ($ per person per year)	(h) 2050 average energy + air quality damage + world climate cost savings due to WWS ($ per person per year)
Virginia	11.1	10.5	11.2	142	1255	676	5501	6898
Washington	9.4	9.0	9.4	85	949	−635	4195	5229
West Virginia	10.6	10.4	9.2	703	1259	172	38911	40 873
Wisconsin	10.1	11.3	10.6	318	1197	−548	9264	10 779
Wyoming	9.9	9.9	8.3	1382	787	−612	75 614	77 783
United States	11.11	10.55	9.78	263	1491	661	8265	10 019

[a] (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 (ESI) 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 ESI and ref. 9, 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).

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.[15]

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 per year, with a range of 12 000–95 000 per year and for O_3 are ∼14 000 premature mortalities per year, with a range of 7000–21 000 per year. Thus, overall, the bottom-up approach gives ∼62 000 (19 000–115 000) premature mortalities per year for $PM_{2.5}$ plus O_3. The top-down estimate (50 000–100 000), from ref. 15, is within the bottom-up range.

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 ESI† and ref. 9.

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 per year to be $600 (85–2400) bil. per year using $13.1 (7.3–23.0) million per 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,

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[a]

State	2012 population	2010–2012 low avoided mortalities per year	2010–2012 mean avoided mortalities per year	2010–2012 high avoided mortalities per year	2050 mean avoided mortalities per year	2050 mean avoided cost ($mil. per year)
Alabama	4 822 023	291	954	1784	596	7799
Alaska	731 449	23	84	155	71	922
Arizona	6 553 255	517	1518	2729	1911	24 988
Arkansas	2 949 131	126	448	859	301	3937
California	38 041 430	3825	12 528	23 194	9778	127 868
Colorado	5 187 582	262	699	1215	568	7428
Connecticut	3 590 347	235	729	1338	393	5142
Delaware	917 092	61	198	367	132	1723
Florida	19 317 568	818	2681	5018	3118	40 770
Georgia	9 919 945	632	2043	3799	1585	20 733
Hawaii	1 392 313	51	192	374	121	1584
Idaho	1 595 728	73	219	395	185	2420
Illinois	12 875 255	942	3150	5909	1811	23 678
Indiana	6 537 334	523	1704	3170	1037	13 562
Iowa	3 074 186	164	540	1010	272	3552
Kansas	2 885 905	121	377	695	220	2878
Kentucky	4 380 415	280	887	1638	542	7089
Louisiana	4 601 893	236	780	1462	465	6075
Maine	1 329 192	43	136	250	71	927
Maryland	5 884 563	436	1350	2475	966	12 630
Massachusetts	6 646 144	328	1033	1906	628	8206
Michigan	9 883 360	565	1744	3192	927	12 129
Minnesota	5 379 139	205	692	1305	475	6213
Mississippi	2 984 926	167	553	1036	320	4186
Missouri	6 021 988	361	1123	2065	700	9156
Montana	1 005 141	37	139	266	81	1054
Nebraska	1 855 525	74	245	460	142	1863
Nevada	2 758 931	212	567	986	632	8261
New Hampshire	1 320 718	54	171	317	119	1557
New Jersey	8 864 590	467	1528	2854	946	12 373
New Mexico	2 085 538	117	353	640	184	2409
New York	19 570 261	901	3137	5963	1708	22 342
North Carolina	9 752 073	543	1672	3065	1485	19 417
North Dakota	699 628	18	57	105	29	385
Ohio	11 544 225	911	2920	5403	1551	20 279
Oklahoma	3 814 820	186	606	1131	412	5383
Oregon	3 899 353	132	453	849	403	5265
Pennsylvania	12 763 536	921	3065	5730	1649	21 563
Rhode Island	1 050 292	53	166	307	87	1131
South Carolina	4 723 723	288	948	1774	663	8667
South Dakota	833 354	26	81	150	45	595
Tennessee	6 456 243	432	1380	2558	1047	13 688
Texas	26 059 203	1294	4217	7869	4142	54 161
Utah	2 855 287	209	598	1060	598	7821
Vermont	626 011	20	62	115	36	473
Virginia	8 185 867	436	1352	2483	1051	13 740
Washington	6 897 012	242	839	1592	832	10 887
West Virginia	1 855 413	101	327	610	147	1920
Wisconsin	5 726 398	294	934	1727	544	7109
Wyoming	576 412	23	62	108	32	417
United States	313 281 717	19 273	62 241	115 461	45 754	598 356

[a] Premature mortality due to ozone exposure is estimated on the basis of the 8 h maximum ozone each day over the period 2010–2012.[29] Relative risks and the ozone-health-risk equation are as in ref. 15. The low ambient concentration threshold for ozone premature mortality is assumed to be 35 ppbv (ref. 15, 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[29] and the relative risks[30] for long-term health impacts of $PM_{2.5}$ are applied to all ages as in ref. 31 rather than to those over 30 years old as in ref. 30. The threshold for $PM_{2.5}$ is zero but concentrations below 8 $\mu g\ m^{-3}$ are down-weighted as in ref. 15. 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 ESI. The cost of avoided mortalities plus associated morbidities is determined as described in the text.

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 (282–1063) per metric tonne-CO_2e in 2013 dollars (ESI†). 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 (ESI†).

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. per year 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. per year). 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 ~\$8300 (4700–17 600) per person per year (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.[33] 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 2080 hours of work per year). This analysis assumes that each year from 2010 to 2050 1/40th of the WWS infrastructure is built.

The JEDI models are economic input–output models that have several uncertainties.[34] To evaluate the robustness of the models, we compared results with calculations derived from a compilation of 15 different renewable energy job creation models.[35] 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

Table 8 Percent of 2010 world CO_2 emissions by state,[32] 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. per year)		
State	Percent of world CO_2 emissions	Medium avoided state climate costs (\$2013 bil. per year)	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	7058.7	3316.1	1869.4

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.

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.

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.[48] 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.[49] 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 per year 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. per year during the construction stage and $132 bil. per year for operation. The annual earnings lost from fossil-fuel industries total ~$270 bil. per year giving a net gain in annual earnings of ~$85 bil. per year.

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%.[50–54]

11. Timeline for implementing the roadmaps

Fig. 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 sector will take a bit longer to convert to WWS because we also need to make changes to the supporting energy-delivery infrastructure, and this is 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.

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 con-struction jobs	40-year operation jobs	Job losses in current energy industry	40-year net con-struction plus operation jobs cre-ated minus jobs lost	Earnings from new 40-year construction jobs ($bil 2013 per year)	Earnings from new 40-year operation jobs ($bil 2013 per year)	Net earnings from new construct-ion plus operation jobs minus jobs lost ($bil 2013 per year)
Alabama	130 925	49 650	57 095	123 480	7.28	3.11	6.40
Alaska	14 662	15 099	24 423	5339	0.87	1.10	0.26
Arizona	49 200	18 536	63 825	3911	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	−6040	2.89	1.48	−0.98
Connecticut	40 487	21 662	34 194	27 955	2.25	1.40	1.27
Delaware	8286	6458	8922	5822	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	8239	4239	13 599	−1120	0.47	0.29	−0.19
Idaho	16 877	6707	14 746	8837	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	5642	16 202	3273	0.79	0.39	0.05
Nebraska	26 533	12 006	23 343	15 196	1.54	0.85	0.75
Nevada	27 457	9140	27 589	9008	1.56	0.60	0.24
New Hampshire	10 402	5697	13 662	2437	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	9663	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	8574	26 690	3628	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	7473	5775	9892	3356	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	4714	8028	6930	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	3902	1.72	0.82	−0.11
Vermont	2496	1005	6455	−2953	0.14	0.07	−0.24
Virginia	89 362	57 779	83 707	63 434	5.14	3.83	3.11

Table 9 (continued)

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 ($bil 2013 per year)	Earnings from new 40-year operation jobs ($bil 2013 per year)	Net earnings from new construction plus operation jobs minus jobs lost ($bil 2013 per year)
Washington	38 226	24 927	67 603	−4449	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	7731	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.

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

Energy technology	Installed MW	Jobs per installed MW		Number of permanent jobs	
		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	3785	10 814
Geothermal plant	20 845	1.67	1.78	34 811	37 103
Hydroelectric plant	3789	1.14	1.14	4319	4319
Tidal turbine	8823	0.14	0.40	1235	3529
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

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	1160[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] Ref. 36. [b] Workers employed in U.S. refineries from ref. 37. 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 ref. 38. [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 ref. 39. All other data from ref. 40. [d] Ref. 41. [e] Sum U.S. uranium mining employment across 12 U.S. states that mine uranium from ref. 42. State values are estimated by multiplying the total by the state population divided by the total population of the 12 states. [f] Ref. 43. [g] Multiply the total number of direct U.S. jobs in transportation (11 000 000) from ref. 44 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 ref. 45 and by the fraction of transportation jobs that are relevant to oil and coal transportation (0.78) from ref. 46 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.[47] [i] See text for discussion of jobs retained.

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 (ref. 6, Section A.2.7) with electric 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.

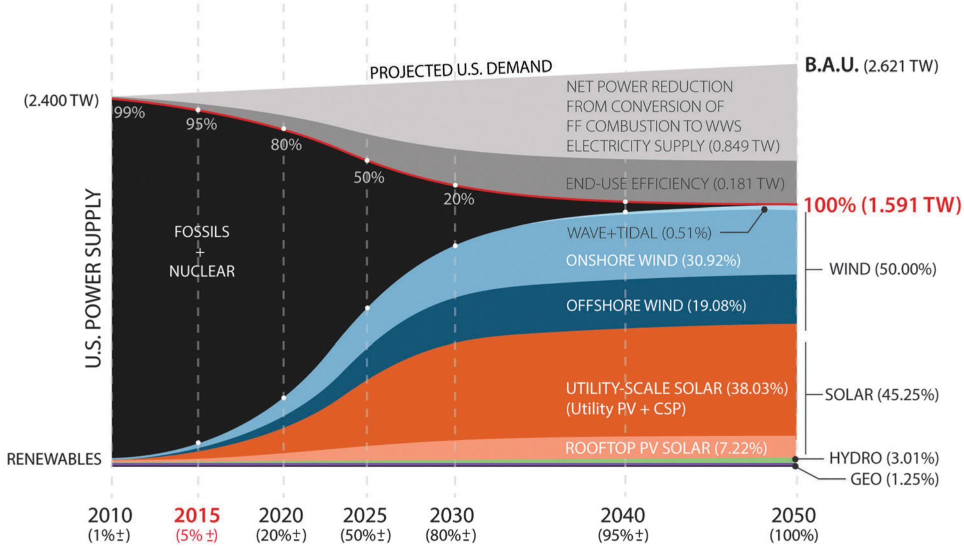

Fig. 5 Time-dependent change in U.S. end-use power demand for all purposes (electricity, transportation, heating/cooling, and industry) and its supply by conventional fuels and WWS generators based on the state roadmaps proposed here. Total power demand decreases upon conversion to WWS due to the efficiency 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.

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.[55] 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.

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[2] 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%), 2273 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%), 8800 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 1364 CSP plants (providing an additional ~4.38% of annually-averaged load) and 9380 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. per year in 2013 dollars and annual earnings during operation of the WWS facilities are estimated at ~$132 bil. per year. Net earnings from construction plus operation minus lost earnings from lost jobs are estimated at ~$85 bil. per year.

The state roadmaps will reduce U.S. air pollution mortality by ~62 000 (19 000–115 000) U.S. air pollution premature mortalities per year today and ~46 000 (12 000–104 000) in 2050, avoiding ~$600 ($85–$2400) bil. per 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. per year 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) per year in energy costs ($2013 dollars), $1500 (210–6000) per year in health costs, and $8300 (4700–17 600) per year 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.

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