Renewable Energy 86 (2016) 75–88

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

A 100% wind, water, sunlight (WWS) all-sector energy plan for Washington State

Mark Z. Jacobson [a, *], Mark A. Delucchi [b], Guillaume Bazouin [a], Michael J. Dvorak [c], Reza Arghandeh [d], Zack A.F. Bauer [a], Ariane Cotte [a], Gerrit M.T.H. de Moor [a], Elissa G. Goldner [a], Casey Heier [a], Randall T. Holmes [a], Shea A. Hughes [a], Lingzhi Jin [a], Moiz Kapadia [a], Carishma Menon [a], Seth A. Mullendore [a], Emily M. Paris [a], Graham A. Provost [a], Andrea R. Romano [a], Chandrika Srivastava [a], Taylor A. Vencill [a], Natasha S. Whitney [a], Tim W. Yeskoo [a]

[a] *Atmosphere/Energy Program, Dept. of Civil and Env. Engineering, Stanford University, USA*
[b] *Institute of Transportation Studies, U.C. Berkeley, USA*
[c] *Sailor's Energy, USA*
[d] *California Institute for Energy and the Environment, U.C. Berkeley, USA*

ARTICLE INFO

Article history:
Received 14 July 2014
Received in revised form
31 July 2015
Accepted 1 August 2015
Available online xxx

Keywords:
Renewable energy
Air pollution
Global warming
Wind
Solar
Energy cost

ABSTRACT

This study analyzes the potential and consequences of Washington State's use of wind, water, and sunlight (WWS) to produce electricity and electrolytic hydrogen for 100% of its all-purposes energy (electricity, transportation, heating/cooling, industry) by 2050, with 80–85% conversion by 2030. Electrification plus modest efficiency measures can reduce Washington State's 2050 end-use power demand by ~39.9%, with ~80% of the reduction due to electrification, and can stabilize energy prices since WWS fuel costs are zero. The remaining demand can be met, in one scenario, with ~35% onshore wind, ~13% offshore wind, ~10.73% utility-scale PV, ~2.9% residential PV, ~1.5% commercial/government PV, ~0.65% geothermal, ~0.5% wave, ~0.3% tidal, and ~35.42% hydropower. Converting will require only 0.08% of the state's land for new footprint and ~2% for spacing between new wind turbines (spacing that can be used for multiple purposes). It will further result in each person in the state saving ~$85/yr in direct energy costs and ~$950/yr in health costs [eliminating ~830 (190–1950)/yr statewide premature air pollution mortalities] while reducing global climate costs by ~$4200/person/yr (all in 2013 dollars). Converting will therefore improve health and climate while reducing costs.

1. Introduction

This paper analyzes a roadmap for converting Washington State's all-purpose (electricity, transportation, heating/cooling, and industry) energy infrastructure to one powered by wind, water, and sunlight (WWS). Existing energy plans in Washington State are largely embodied in the 2012 Washington State Energy Strategy and Biennial Energy Reports [48]. Both address the need to reduce greenhouse gas emissions, keep energy prices low, and foster jobs. However, the goals in those reports are limited to emission reductions based on a 2008 state law that requires reducing statewide greenhouse gas emissions to 1990 levels by 2020, to 25% below 1990 levels by 2035, and to 50% below 1990 levels by 2050. The plan proposed here outlines not only how to achieve Washington State's current goals but also how to achieve much more aggressive goals: eliminating 80–85% of present-day greenhouse-gas and air-pollutant emissions by 2030 and 100% by 2050.

Several previous studies have analyzed proposals for near 100% WWS penetration in one or more energy sectors of a region (e.g. Refs. [23,24,19,5,3,31,2,30]). The plan proposed here is similar in outline to ones recently developed for New York State and California [25,26]. However, the estimates of energy demand, potential supply, and proposed policy measures here are developed specifically for Washington State, which has greater installed hydropower and thus more built-in storage for matching power supply

---

[*] Corresponding author.
E-mail address: Jacobson@stanford.edu (M.Z. Jacobson).

http://dx.doi.org/10.1016/j.renene.2015.08.003
0960-1481/© 2015 Elsevier Ltd. All rights reserved.

with demand than do New York or California. This paper also includes originally-derived (1) computer-simulated resource analyses for both wind and solar in Washington State, (2) air-pollution mortality calculations considering air quality data at all air-quality monitoring stations in the state, (3) estimates of cost reductions associated with avoided air pollution mortality and morbidity, (4) potential job creation versus loss numbers for the state, (5) estimates of the future cost of energy and of avoided global climate costs, (6) and a WWS supply breakdown in the state based on 2050 energy demand. It further provides a transition timeline and develops policy measures specifically for Washington State.

2. How the technologies were chosen

The WWS energy technologies chosen here are existing technologies ranked the highest among several proposed options for addressing air and water pollution, global warming, and energy security [20]. For electricity generation, the primary technologies include wind, concentrated solar power (CSP), geothermal, solar photovoltaics (PV), tidal, wave, and hydropower.

The main ground-transportation technologies are battery electric vehicles (BEVs) and hydrogen fuel cell (HFC) vehicles, where the hydrogen is produced by electrolysis (electrolytic hydrogen) from WWS electricity. BEVs with fast charging or battery swapping will dominate long-distance, light-duty ground transportation; battery electric-HFC hybrids will dominate heavy-duty ground transportation and long-distance water-borne shipping; batteries will power short-distance shipping (e.g., ferries); and electrolytic cryogenic hydrogen, combined with batteries used for idling, taxiing, and internal power, will power aircraft. Note that we restrict the use of HFCs to transport applications that require more on-board energy storage than can be provided economically by batteries — long-distance, heavy-load ground transport, shipping, and air transport — because electrolytic HFCs are a relatively inefficient use of primary WWS power. We do not use electrolytic hydrogen and HFCs to generate electricity because, as we discuss later, there are more economical ways to balance supply and demand in a 100% WWS system.

Air heating and cooling will be electrified and powered by electric heat pumps (ground-, air-, or water-source) and some electric-resistance heating. Water heat will be generated by heat pumps with electric resistance elements and/or solar hot water preheating. Cook stoves will have either an electric induction or a resistance-heating element. High-temperature industrial processes will be powered by electric arc furnaces, induction furnaces, dielectric heaters, resistance heaters, and some combusted electrolytic hydrogen.

Our plan assumes the adoption of new energy-efficiency measures, but it excludes the use of nuclear power, coal with carbon capture, liquid or solid biofuels, or natural gas because they all result in more air pollution and climate-relevant emissions than do WWS technologies and have other problems, as discussed in Refs. [24,25].

3. Changes in Washington State power demand upon conversion to WWS

Table 1 summarizes estimated Washington State end-use power demand (load) in 2010 and 2050 if conventional fuel use continues along a business-as-usual (BAU) or conventional energy trajectory and following a conversion to a 100% WWS infrastructure (zero fossil fuels, biofuels, or nuclear fuels). End-use power is the power in electricity or fuel (e.g., power available in gasoline) that people actually use to provide heating, cooling, lighting, transportation, and so on. Thus, it excludes losses incurred during the production and transmission of the power. In the WWS case, all end uses that feasibly can be electrified are assumed to use WWS power directly, and remaining end uses (some high-temperature industrial processes, and some transportation) are assumed to use WWS power indirectly in the form of electrolytic hydrogen. Under these assumptions, electricity requirements will increase, but the use of oil, gas, coal, uranium, and biofuels will decrease to zero. Further, the increase in electricity use will be much smaller than the decrease in energy embodied in conventional fuels because of the high efficiency of electricity for heating and electric motors. As a result, end use power demand will decrease significantly in a WWS world (Table 1).

Table 1 indicates that the power required to satisfy all end-use demand in Washington State for all purposes in 2010 was ~46 GW (gigawatts, billion watts). In 2010, delivered electricity was about 10.3 GW of all-purpose end-use power. If Washington State follows its current trajectory of fossil-fuel growth, all-purpose end-use power demand will increase to ~52.8 GW by 2050 (Table 1). A conversion to WWS by 2050 is estimated to reduce Washington State total end-use power demand by ~39.9%, with the greatest percentage reduction occurring in the transportation sector. About 7.4% points of this reduction is due to modest end-use energy efficiency measures beyond those in the BAU scenario, and another small portion is due to the fact that conversion to WWS eliminates the use of energy during coal, oil, gas, and uranium mining, transport, and refining. The remaining and major reason for the reduction in end-use energy demand is that the use of electricity for heating and electric motors is more efficient than is fuel combustion for the same applications. Also, while the use of WWS electricity to produce hydrogen for HFC vehicles is less efficient than is the use of WWS electricity to run BEVs, it is more efficient and cleaner than is burning liquid fossil fuels for vehicles [22]. The values in Table 1 also take into account the fact that combustion of electrolytic hydrogen for heat, while cleaner, is slightly less efficient than is combustion of fossil fuels for heat.

4. Numbers of electric power generators needed and land-use implications

Table 2 summarizes one of several possible 2050 scenarios providing the all-purpose end-use power in Washington State assuming the end-use power requirements in Table 1 and accounting for electrical transmission and distribution losses. In the scenario, the power is supplied by ~35.0% onshore wind, ~13.0% offshore wind, ~10.73% utility-scale PV, ~2.9% residential PV, ~1.5% commercial/government PV, ~0.65% geothermal, ~0.5% wave, ~0.3% tidal, and ~35.42% hydropower. The plan proposes no concentrated solar power (CSP) installed in Washington State, since it will be more efficient to install CSP in states with more direct solar radiation exposure. PV, on the other hand, can be efficient when exposed to diffuse and/or direct radiation.

Rooftop PV 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. Utility-operated PV power plants are sized, on average, relatively small (50 MW) to allow them to be placed optimally in available locations.

Wind (48.0%), hydropower (35.42%), and solar (15.13%) are the largest generators of end-use electric power in the state under this plan. The use of all three in combination is needed to help ensure reliability of the grid (Section 6). The ratio of wind to solar end-use power is ~3.2:1. Wind is currently less expensive than solar, particularly under Washington State solar conditions, and is therefore proposed to play a larger role there than is solar. The

Table 1

Contemporary (2010) and projected (2050) end-use power demand (GW of delivered power = GWh/yr of energy production divided by 8760 h/yr) for all purposes by sector, for Washington State if conventional fossil-fuel, uranium, and biofuel use continue as projected (BAU) or if 100% of conventional fuels are replaced with wind–water–solar (WWS) technologies by 2050. Also shown are the percent differences in the 2050 WWS minus BAU cases.

Sector	BAU		WWS	2050 Difference
	2010	2050	2050	%
Residential	7.5	7.54	5.61	−25.5
Commercial	5.7	8.02	6.74	−15.9
Industrial	12.4	15.9	12.3	−22.9
Transportation	20.5	21.3	7.09	−66.7
Total	46.0	52.8	31.7	−39.9

The table is derived in the spreadsheet [8].

installed capacity of hydropower is assumed to remain fixed between 2010 and 2050. However, hydropower dams are assumed to run slightly more efficiently for producing peaking power, thus the capacity factor of hydropower is assumed to increase.

Table 2 lists installed capacities for solar thermal collectors to collect heat to be stored in soil, for the purpose of meeting seasonal

Table 2

Number, capacity, footprint area, and spacing area of WWS power plants or devices needed to provide Washington State's total annually-averaged end-use power demand for all purposes in 2050, accounting for transmission, distribution, forced and unforced maintenance, and array losses. Ref. [8] contain the derivations for this table.

Energy technology	Rated power one plant or device (MW)	[a]Percent of 2050 all-purpose load met by plant/device	Name-plate capacity, existing plus new plants or devices (MW)	Percent name-plate capacity already installed 2013	Number of new plants or devices needed for state	[b]Percent of state land area for footprint of new plants or devices	Percent of state land area for spacing of new plants or devices
Annual power							
Onshore wind	5	35.0	40,930	6.86	7624	0.000056	1.97
Offshore wind	5	13.0	10,608	0.0	2122	0.000015	0.547
Wave device	0.75	0.5	733	0.0	977	0.000298	0.0142
Geothermal plant	100	0.65	242	0.0	2.4	0.000482	0
Hydropower plant[c]	1300	35.42	21,510	100.0	0.0	0	0
Tidal turbine	1	0.3	387	0.0	387	0.000065	0.0008
Res. roof PV	0.005	2.9	6774	0.12	1,353,000	0.029364	0
Com/gov roof PV[d]	0.1	1.5	3141	0.13	31,367	0.013614	0
Solar PV plant[e]	50	10.73	18,081	0.02	372	0.078457	0
Total		100.0	102,406	23.8		0.13	2.53
Peaking/storage							
Solar thermal[f]	50	2.60	4404	0	88	0.0037	0
Total all			106,810	22.8		0.152	2.53
Total new land[g]						0.08	1.97

The number of devices in Washington State is the end use load in 2050 in each state (Table 1) multiplied by the fraction of load satisfied by each source in the state (this table) and divided by the annual power output from each device. The annual power output equals the rated power (this table) multiplied by the annual capacity factor of the device after accounting for transmission, distribution, forced and unforced maintenance, and array losses. The capacity factor is determined for each device in the state as in Ref. [8]. The capacity factor for onshore wind turbines in 2050, accounting for transmission, distribution, maintenance, and array losses, is calculated from actual 2013 state installed capacity [9] and power output, then assuming an 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 sites are taken. The 2050 Washington State onshore wind mean capacity factor calculated in this manner (after losses) is 27.5%. Offshore wind turbines are assumed to be placed in locations with hub-height wind speeds of 8.5 m/s or higher [10], which corresponds to a capacity factor before transmission, distribution, maintenance, and array losses of ~42.5% for the same turbine and 38.9% after losses. Short- and moderate distance transmission, distribution, and maintenance 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, which are due to the reduction in kinetic energy available to downstream turbines in an array, are an additional 8.5%. The plan assumes 38 (30–45)% of onshore wind and solar and 20 (15–25)% of offshore wind is subject to *national* long-distance high-voltage direct current transmission with line lengths of 1400 (1200–1600) km and 120 (80–160) 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 as in Ref. [8]. Footprint is the area on the top surface of soil covered by an energy technology, thus does not include underground structures nor space between devices.

[a] Total Washington State end-use load with 100% WWS in 2050 is estimated as 31.7 GW (Table 1).

[b] Total Washington State land area is 172,350 km^2.

[c] The average capacity factor for hydropower is assumed to increase from its current value to 52.2% (see text).

[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 assumed to be 13–14% and 15%, respectively, after losses, which are at the low end of estimated capacity factors of 16–30% for Northwest U.S. solar [39].

[e] For utility solar PV plants, nominal walking space between panels is included in the plant footprint area. The capacity factors assumed for utility PV are 18.0%–19.0%.

[f] The installed capacity for peaking power/storage is derived in the grid integration study of Ref. [27]. Solar thermal is used for soil heat storage.

[g] The footprint area requiring new land is equal to the footprint area for new onshore wind, geothermal, and utility solar PV. Offshore wind, wave and tidal are in water, and so do not require new land, and the plan includes no new hydropower plants. The footprint area for rooftop solar PV does not entail new land because the rooftops already exist. 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.

heating loads. The corresponding soil storage also is needed to store excess electricity to ensure reliability of the grid, as described and quantified in the grid integration study of Ref. [27].

Fig. 1 illustrates the additional footprint and spacing areas from Table 2 required for Washington State to replace its entire all-purpose energy infrastructure with WWS in 2050. Footprint area is the physical area on the top soil (thus not underground) needed for each energy device. Spacing area is the area between some devices, such as wind, tidal, and wave power, needed, for example, to minimize interference of the wake of one turbine with downwind turbines.

Table 2 indicates that the total new land footprint required for this plan is ~0.08% of Washington State's land area, almost all for utility-scale solar PV plants (rooftop solar does not take up new land). This does not account for the footprint reduced from eliminating the current energy infrastructure, including the footprint required for mining, transporting, and refining fossil fuels and uranium and for growing, transporting, and refining biofuels.

The present plan requires a spacing area equivalent to ~1.97% of Washington States' land area for onshore wind turbines (Table 2). This spacing footprint is relatively small, and in any case the spacing area can be used for multiple purposes, such as agricultural land, grazing land, or open space. Landowners can thus derive income not only from the wind turbines on the land but also from farming around the turbines.

For several reasons, we have not estimated the footprint or spacing area of any additional transmission line. Transmission systems have virtually no footprint on the ground because transmission towers are four metal supports connected to small foundations, allowing grass to grow under the towers. The right-of-way under transmission lines typically can accommodate many uses; certainly more uses than in the right-of-way for gas and oil pipelines and other conventional infrastructure that transmission lines will replace. Finally, in our plan as much additional transmission capacity as possible will be along existing pathways but with enhanced lines.

5. Resource availability

Washington State has more wind, solar, geothermal, and hydropower resources than is needed to supply the state's all-purpose energy in 2050. In this section, WWS resources are examined.

5.1. Wind

Fig. 2 shows 3-D computer model estimates, derived for this study, of Washington State's annual capacity factor of onshore and offshore wind turbines. The calculations were performed assuming REpower (Senvion) 5 MW turbines with 126-m rotor diameters (D). Model results were obtained for a hub height of 100-m above the

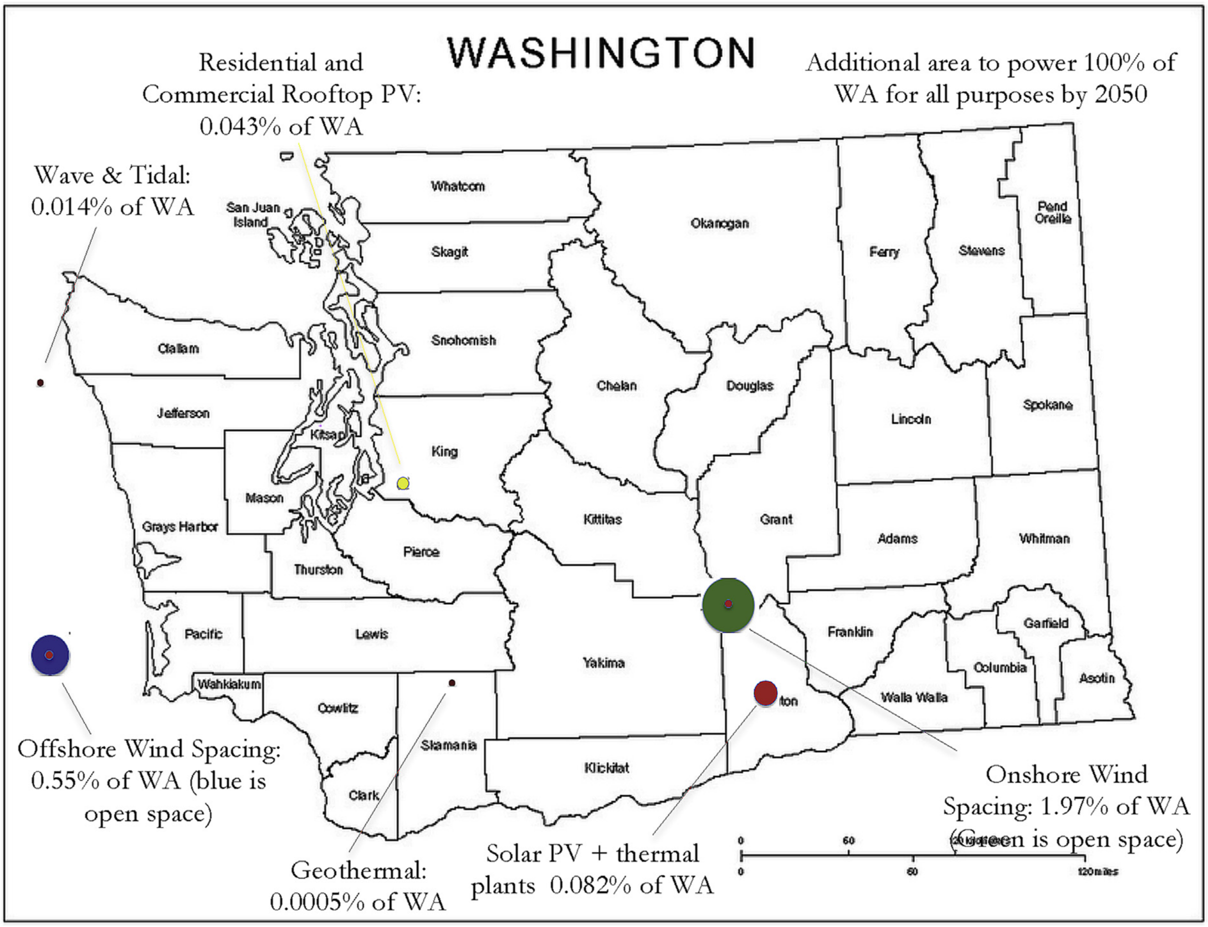

Fig. 1. Spacing and footprint areas needed for new plants and devices from Table 2 to repower Washington State for all purposes in 2050. The dots do not indicate the actual location of energy farms. For wind, the small red dot in the middle is footprint on the ground (not to scale) and the green or blue is space between turbines. For others, footprint and spacing are the same. For rooftop PV, the dot represents the rooftop area needed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

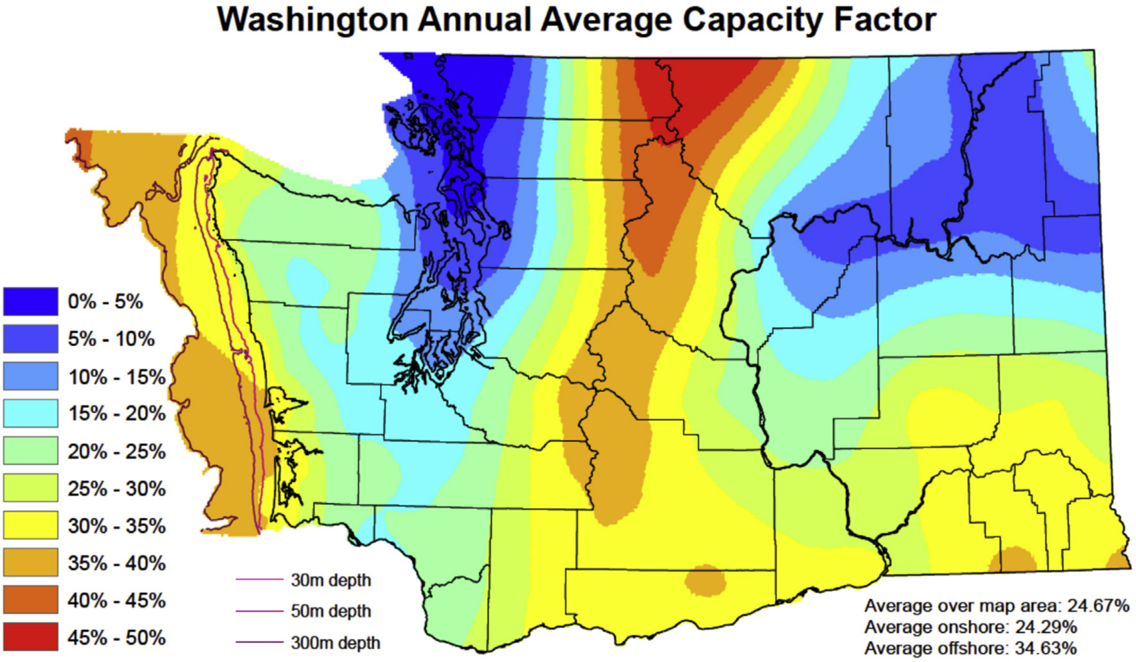

Fig. 2. Modeled 2006 annually averaged capacity factor for a 5 MW RePower (Senvion) wind turbine (126-m diameter rotor) at 100-m hub height above the topographical surface in Washington State. Results at 100 m above topography from two models were merged into the same figure. For onshore wind, the model used was GATOR-GCMOM [21], which was 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. For offshore winds out to 400-m depth, the NCAR Weather Research Forecast (WRF) model was used at 5 km × 5 km resolution for a five-year period (M. Dvorak, personal communication).

topographical surface. Spacing areas between turbines were 4D × 7D for onshore wind and 5D × 10D for offshore wind. Results suggest that Washington State's onshore wind potential at 100 m hub height in locations with capacity factor >30% may be ~663 GW of installed capacity, or 1860 TWh/yr of delivered energy. This significantly exceeds the installed capacity of 40.9 GW needed to provide 35% of Washington State's 2050 all-purpose power from onshore wind (Table 2).

Washington State's offshore wind resources are found to support ~3.4 GW, ~3.7 GW, and ~53.3 GW of installed capacity in water depths of <30 m, 30–50 m, and 50–300 m depths, respectively (Fig. 2). Averaged over the year, the total installed capacity potential is thus ~60.5 GW, which far exceeds the proposed offshore installed wind power needed in Table 2 of 10.6 GW. For <30 m depth, the range for current offshore wind turbines, standard monopole or gravity base foundation are used. For 30–50 m depth, a tripod or jacket foundation is used. For depth >50 m, floating offshore structures are needed.

5.2. Solar

The best solar resources in Washington State are in the south-central part followed by the southeastern part of the state. Fig. 3 shows an average solar insolation of 3.4–4.5 kWh/m^2/day in the state, relatively consistent with previous analyses (e.g., [49]). Based on Table 2, only 0.08% of the state's land is needed for solar PV power plants and solar thermal collectors (for soil heat storage) in 2050.

Table 3 provides the maximum rooftop areas available suitable for PV and the percent penetration of rooftop PV based on the proposed installed rooftop PV capacities given in Table 2. The table indicates that less than 50% of rooftop PV potential for the state will be used under the roadmap, suggesting room for its further growth past 2050 or the use of more rooftop PV instead of offshore wind, for example.

5.3. Geothermal

The roadmap calls for geothermal to supply 210 MW of end-use power in 2050 to Washington State. The state has 23 MW of identified end-use power from geothermal, 300 MW of undiscovered end-use power from geothermal, and 6500 MW of enhanced recovery end-use power [47]. About 50–600 MW of geothermal potential (for heating and electricity) exists in the Columbia River basin alone [18,34].

5.4. Hydropower

In 2011, Washington State produced more electricity from hydropower than any other state, accounting for ~29% of the U.S. total hydropower output. Hundreds of dams line the Columbia and Snakes rivers that flow through Washington State. The largest is the Grand Coulee Dam on the Columbia River, which is also the largest hydropower dam in the U.S., with a generation capacity of 6809 MW.

In 2010, conventional hydropower supplied 7.80 GW (68,288 GWh/yr) of delivered electricity in Washington State, representing 69.5% of the state's electricity supply [11]. The installed conventional hydropower capacity was 21.181 GW [11], which included large (>30 MW) and small (<30 MW) hydropower, including run-of-the-river hydropower. Thus, the capacity factor of conventional hydropower was 36.8% in 2010.

In addition, Washington State received an estimated 0.184 GW of delivered hydropower from British Columbia. Using a capacity factor of 56.47%, we assign Canadian hydropower coming to Washington State an approximate installed capacity of 0.326 GW. We include this as part of existing hydropower capacity in Washington State in Table 2 (for a total existing Washington State hydropower capacity of 21.51 GW) to account for the fact that this may continue to 2050.

Under the plan proposed here, conventional hydropower will

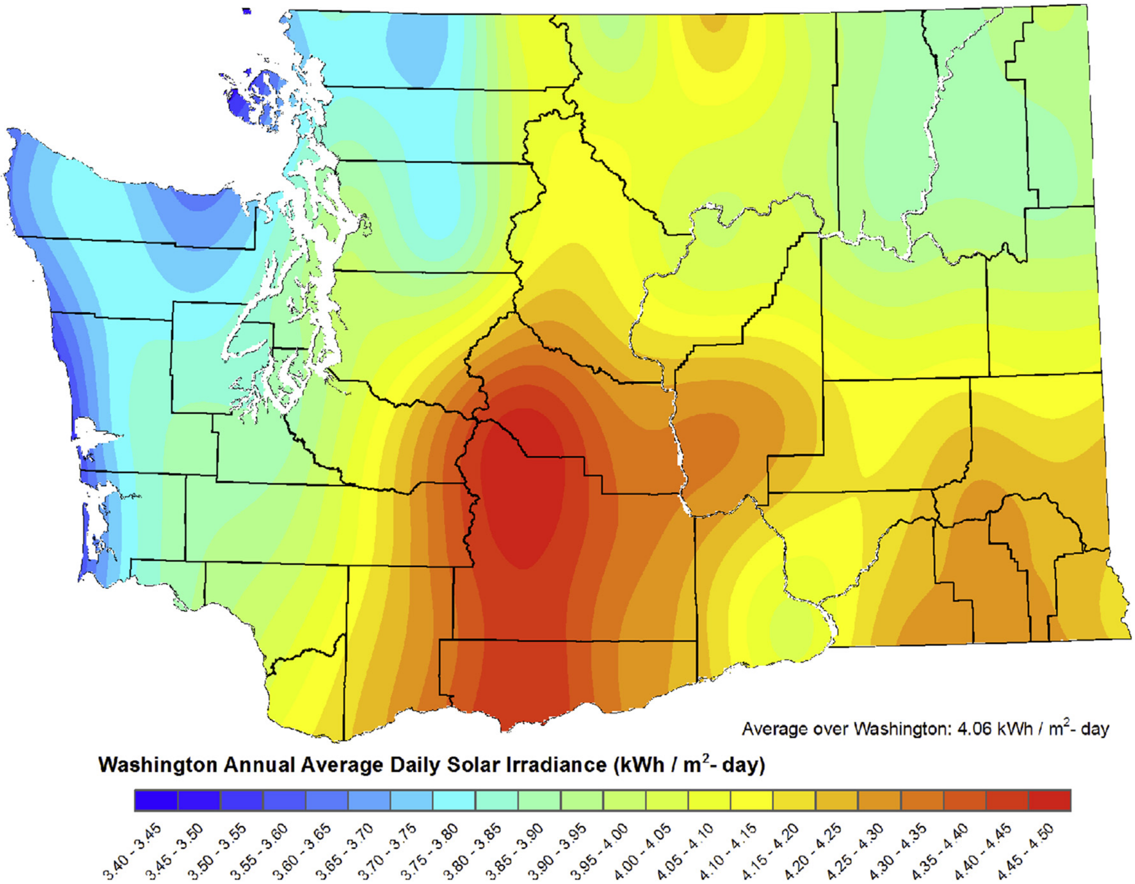

Fig. 3. Modeled 2013 annual downward direct plus diffuse solar radiation at the surface (kWh/m^2/day) available to photovoltaics in Washington State and neighboring states. The model used was GATOR-GCMOM [21], which simulates clouds, aerosols gases, weather, radiation fields, and variations in surface albedo over time. The model was nested from the global to regional scale with resolution on the regional scale relatively coarse (0.6 °. W–E × 0.5°. S–N).

supply 11.23 GW of delivered power, or 35.42% (Table 2) of Washington State's 2050 total end-use power demand for all purposes Thus, 2010. Washington State plus Canadian delivered hydropower (7.984 GW) already provides 71.1% of Washington State's 2050 delivered hydropower power goal. The plan here calls for no new hydropower installations (Table 2); instead, the additional 3.25 GW of delivered hydropower will be obtained by increasing the capacity factor of existing hydropower in Washington State to 52.2%, since current hydropower provides much less than its maximum capacity due to an oversupply of energy available from other sources and multiple priorities affecting water use.

5.5. *Tidal power*

Tidal (or ocean current) is proposed to provide ~0.3% (100 MW) of Washington State's total end-use power in 2050 (Table 2). Washington State currently has the potential to generate 683 MW of end-use power from tides in the Columbia River, Willapa Bay, Gray's Harbor and Admiralty Inlet Entrance regions. Thus enough tidal power exists to meet the needed load.

5.6. *Wave power*

Wave power is also proposed to comprise 0.5%, or about 160 MW of Washington State's total end-use power demand in 2050 (Table 2). Washington State has a potential of 8.2 GW (72 TWh/yr) [17] of delivered wave power along the inner continental shelf, over 50 times the delivered power needed under this plan.

6. Matching electric power supply with demand

A critical need for a 100% renewable energy plan is to ensure reliability of the grid. To that end [27] develop and apply a grid integration model to determine the quantities and costs of storage devices needed to ensure that a 100% WWS system developed for

Table 3
Rooftop areas suitable for PV panels, potential capacity of suitable rooftop areas, and proposed installed capacities for both residential and commercial/government buildings in Washington State. Calculated with the methodology given in Ref. [26].

	Rooftop area suitable for PV in 2012 (km^2)	Potential capacity of suitable area in 2050 (MW$_{\text{dc-peak}}$)	Proposed installed capacity in 2050 (MW$_{\text{dc-peak}}$)	Percent of potential capacity installed
Residential	73.6	14,050	6774	48
Commercial/govt.	37.2	7180	3141	44

each of the 48 contiguous U.S. states, when integrated across all such states, can match load without loss every 30 s for 6 years (2050–2055) while accounting for the variability and uncertainty of WWS resources.

Wind and solar time-series in that study are derived from 3-D global weather model simulations that account for extreme events and competition among wind turbines for kinetic energy. Solutions are obtained by prioritizing storage for heat (in soil and water), cold (in ice), and electricity (in phase-change materials, hydropower, pumped hydropower storage, and hydrogen), and using demand response.

Washington State's contribution to electric power storage in that study includes hydropower and pumped hydropower storage. Existing hydropower installations are proposed here to supply 35.4% of Washington State's annually averaged end-use power (Table 2) and 21.5 GW of peaking power. Washington State also currently has 0.314 GW of pumped hydropower storage installed in the form of reservoir pairs [11], where water is pumped to a higher reservoir at times of low peak demand and cost and used to generate electricity at times of high peak demand.

Much of Washington State's 2050 WWS load in Table 1 is heat load. This load will be satisfied partly from electricity and partly from heat obtained from 4400 50-MW solar thermal collectors, requiring 0.0037% of the state's land area (Table 2). Such heat will be either used immediately or stored in soil. Excess WWS electricity will also be converted to heat to be stored in water or soil or to be used to produce ice for cooling.

Additional excess electricity will be used to produce hydrogen, another form of storage, which can be used at any time, mainly for transportation. In addition, demand response will be used to shift times of peak load.

Frequency regulation of the grid will be provided by ramping up/down hydropower and pumped hydropower generation, ramping down other WWS generators and storing the electricity in water, soil, or hydrogen instead of curtailing generation, and using demand response.

Multiple low-cost stable solutions to the grid integration problem across the 48 contiguous U.S. states, including Washington State, are obtained in Ref. [27]; suggesting that maintaining grid reliability upon 100% conversion to WWS is a solvable problem. The mean U.S.-averaged levelized cost of energy in that study, accounting for storage transmission, distribution, maintenance, and array losses, is ~10.6 ¢/kWh for electricity and ~11.4 ¢/kWh for all energy in 2013 dollars. Washington State costs are discussed next.

7. Costs of generation

Table 4 presents 2050 estimates of fully annualized, unsubsidized business (private) costs of electric power generation in Washington State for WWS technologies derived in the accompanying spreadsheet analysis [8]. The costs include capital, land, operating, maintenance, transmission, and distribution costs. They do not include the cost of storage, except to the extent hydropower is a form of storage. The estimates are based on current cost data and trend projections for individual generator types. The table indicates that the 2050 business costs of hydropower, onshore wind, utility-scale solar, and solar thermal for heat will be the lowest among the WWS technologies.

Table 4
Approximate fully annualized, unsubsidized 2050 U.S. averaged generation, transmission, distribution, and storage costs for WWS power (2013 U.S. $/kWh-delivered), excluding externality costs. From Ref. [8].

Technology	Technology year 2050		
	LCHB	HCLB	Average
Geothermal	0.081	0.131	0.106
Hydropower	0.055	0.093	0.074
Onshore wind	0.064	0.101	0.082
Offshore wind	0.093	0.185	0.139
PV utility crystalline tracked	0.061	0.091	0.076
PV commercial rooftop	0.072	0.122	0.097
PV residential rooftop	0.080	0.146	0.113
Wave power	0.156	0.407	0.282
Tidal power	0.084	0.200	0.142
Solar thermal for heat ($/kWh-th)	0.051	0.074	0.063

LCHB = low cost, high benefits; HCLB = high cost, low benefits. The costs assume $0.0115 (0.11–0.12)/kWh for standard transmission for all technologies except rooftop solar PV (to which no transmission cost is assigned) and $0.0257 (0.025–0.0264)/kWh for distribution for all technologies. Transmission and distribution losses are accounted for in the energy available.

Table 5 shows the Washington-State-averaged BAU and WWS electric power system costs and comparative energy, air pollution, climate, and total cost savings per person in 2050 upon converting to WWS. The electric power cost of WWS in 2050 is not directly comparable with the BAU electric power cost, because the BAU cost does not integrate transportation, heating/cooling, or industry energy costs. Conventional vehicle fuel costs, for example, are a factor of 4–5 higher than electricity for BEVs, yet the BAU electricity cost in 2050 does not include the transportation cost, whereas the WWS electricity cost does. Nevertheless, although the delivered electricity cost with WWS may be slightly higher than that with conventional fuels in Washington State in 2050, the direct cost of electricity per person is lower with WWS because less energy is needed to perform the same work with WWS because of the efficiency of electricity over combustion (Table 1). Further, the 2050 WWS electricity cost per kWh in Washington State will be lower than the U.S. average cost from the grid integration study (Section 6).

Table 5 also shows the significant health and climate cost savings per person with WWS over BAU, discussed in Section 8. The total up-front capital cost of the 2050 WWS system is ~$163.7 billion for 82.5 GW of new installed capacity (~$1.98 million/MW).

8. Air pollution and global warming damage costs eliminated by WWS

A conversion to a 100% WWS energy infrastructure in Washington State will nearly eliminate energy-related air pollution mortality and morbidity and the associated health costs in the state. It will also nearly eliminate energy-related climate change costs to the U.S. and the world. This section quantifies these benefits.

8.1. Air pollution cost reductions due to WWS

To estimate air pollution mortality and its costs in Washington State, we use a top–down approach and a bottom–up approach.

8.1.1. The top–down approach to estimate air-pollution mortality in Washington State

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. Braga et al. [1] estimate the U.S. air pollution mortality rate as ~3% of the all-cause death rate, which is about 833 deaths per 100,000 people. The U.S. population in 2012 was 313.9 million. This suggests a contemporary air pollution mortality rate in the U.S. of ~78,000/year. Similarly, Jacobson [21] estimates the U.S. premature mortality rate due to ozone and particulate matter to be 50,000–100,000 per year based on three-dimensional air pollution–weather model calculations. These results are consistent with those from Ref. [32]; who estimated 80,000 to 137,000 due to all

Table 5
Washington State mean levelized costs of energy (LCOE) for conventional fuels (business as usual – BAU) in 2013 and 2050 and for WWS fuels in 2050. The LCOE estimates do not include externality costs. Also shown are state health-cost savings and global climate-cost savings per person in Washington State per year (Section 8) due to converting the state to WWS.

(a) 2013 LCOE BAU (¢/kWh)	9.4
(b) 2050 LCOE BAU (¢/kWh)	9.0
(c) 2050 LCOE of WWS (¢/kWh)	9.4
(d) 2050 delivered electricity BAU (TWh/yr)	120.54
(e) 2050 delivered electricity WWS replacing BAU electricity (TWh/yr)	100.08
(f) 2050 avg. energy cost savings per person per year with WWS ($2013/person/yr)	85
(g) 2050 avg. air quality health cost savings with WWS ($2013/person/yr)	949
(h) 2050 avg. climate cost savings to world with WWS ($2013/person/yr)	4195
(i) 2050 avg. energy + health + global climate cost savings with WWS ($2013/person/yr)	5229

a) The 2013 LCOE cost of conventional fuel combines the estimated mix of conventional generators in 2013 with 2013 mean LCOEs for each generator from Ref. [8]. Costs include all-distance transmission, pipelines, and distribution, but not externalities.
b) Same as (a), but for 2050. The BAU case includes significant existing WWS (mostly hydropower) plus future increases in WWS and energy efficiency.
c) The 2050 LCOE of WWS combines the 2050 distribution of WWS generators from Table 2 with the 2050 mean LCOEs for each WWS generator from Table 4. It accounts for all-distance transmission and distribution.
d) Projected delivered electric power in 2050 BAU case.
e) Projected delivered electric power in 2050 WWS case to supply only the electricity from the BAU case.
f) Equals the total cost of electricity use in the electricity sector in the BAU scenario (which equals the product of BAU electricity use and LCOE) less the same in the WWS scenario and less the annualized cost of the assumed efficiency improvements in the electricity sector in the WWS scenario, all divided by 2050 population (11,472,193) (see Ref. [8]; for details).
g) From Table 7.
h) From Table 8.
i) The sum of (f), (g), and (h).

anthropogenic air pollution in the U.S. in 1990, when air pollution levels were higher than today.

The population of Washington State in 2012 was 6.9 million, or 2.2% of the U.S. population. A simple scaling of population to the U.S. premature mortality rate from Ref. [21] yields 1100–2200 annual premature deaths in Washington State from the top–down approach.

8.1.2. The bottom–up approach to estimate air-pollution mortality in Washington State

This approach involves combining measured concentrations of particulate matter ($PM_{2.5}$) and ozone (O_3) with a relative risk per unit concentration and with population. From these three pieces of information, estimates of mortality due to $PM_{2.5}$ and O_3 pollution can be calculated with a health-effects equation (e.g., [21]).

Table 6 shows the resulting bottom–up low, medium, and high estimates of premature mortality in Washington State due to $PM_{2.5}$ and ozone for 2010–2012. The values for the state as a whole are ~720 (180–1420) premature mortalities/yr for $PM_{2.5}$ and ~120 (60–180) premature mortalities/yr for O_3, giving a total of ~840 (240–1590) premature mortalities/year for $PM_{2.5}$ plus O_3. The top–down estimate (1100–2200), determined by scaling the U.S. air pollution premature mortality rate by Washington State population, overlaps but is higher than the bottom–up range because the top–down approach does not account for the lesser severity of air pollution in Washington State cities per capita than in average U.S. cities.

Premature mortality due to ozone exposure is estimated based on the 8-hr maximum ozone each day over the period 2010–2012 [4]. Relative risks and the ozone-health-risk equation are as in Ref. [21]. The low ambient concentration threshold for ozone premature mortality is assumed to be 35 ppbv [21] 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 [4] and the relative risks for long-term health impacts $PM_{2.5}$ [38] applied to all ages as in Ref. [28] rather than those over 30 years old as in Ref. [38]. The threshold for $PM_{2.5}$ is zero but concentrations below 8 $\mu g/m^3$ are down-weighted by a factor of four as in Ref. [21]. For each county in the 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 $PM_{2.5}$, data are not available for 3% of the population and for ozone, data are not available for 36% of the population. For these populations, mortality rates are set equal to the minimum county mortality rate within the 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).

Table 7 provides an estimate of the avoided 2050 premature mortalities upon converting to WWS in Washington State. The estimate accounts for both increases in population and efficiencies in conventional technologies system. The combination of such changes results in slightly fewer mortalities avoided in 2050 versus 2010–2012 upon conversion to WWS.

8.1.3. Mortality and non-mortality costs of air pollution

The mortality cost is equal to the number of mortalities multiplied by the value per mortality. In general, the value of life is determined by economists based on what people are willing to pay to avoid health risks [40,45,29] provide a central estimate for the statistical value of a human life at $7.7 million in 2007 dollars (based on 2000 GDP). Other costs due to air pollution include increased illness (morbidity from chronic bronchitis, heart disease, and asthma), hospitalizations, emergency-room visits, lost school days, lost work days, visibility degradation, agricultural and forest damage, materials damage, and ecological damage [46]. estimates that these non-mortality-related costs comprise an additional ~7% of the mortality-related costs. These are broken down into morbidity (3.8%), recreational plus residential visibility loss (2.8%), agricultural plus forest productivity loss (0.45%), and materials plus ecological loss (residual) costs. However, [32] found that the

Table 6
Washington State annually-averaged, daily-averaged $PM_{2.5}$ concentration; maximum 8-h ozone level averaged over 2010–2012 by country; 2012 population; and resulting annual number of premature mortalities during 2010–2012.

County	$PM_{2.5}$ (μg/m^3)	O_3 (ppbv)	Population (2012)	Annual premature mortalities from $PM_{2.5}$ and ozone					
				Low estimate		Medium estimate		High estimate	
				$PM_{2.5}$	O_3	$PM_{2.5}$	O_3	$PM_{2.5}$	O_3
Adams	5.0	n/a	19,005	0.3	0.1	1.0	0.1	2.0	0.2
Asotin	7.9	n/a	21,888	0.6	0.1	2.5	0.1	4.9	0.2
Benton	6.1	n/a	182,398	3.4	0.6	13.4	1.1	26.5	1.7
Chelan	9.6	n/a	73,687	3.4	0.2	12.9	0.5	24.5	0.7
Clallam	6.6	36.3	71,863	1.4	0.6	5.7	1.3	11.3	1.9
Clark	7.4	33.4	438,287	11.8	3.1	46.5	6.3	91.0	9.4
Columbia	5.2	n/a	3995	0.1	0.01	0.2	0.02	0.4	0.04
Cowlitz	4.9	n/a	101,996	1.4	0.3	5.4	0.6	10.7	0.9
Douglas	n/a	n/a	39,350	0.4	0.1	1.5	0.2	3.0	0.4
Ferry	n/a	n/a	7705	0.1	0.02	0.3	0.05	0.6	0.1
Franklin	5.6	n/a	85,845	1.4	0.3	5.4	0.5	10.7	0.8
Garfield	n/a	n/a	2228	0.02	0.01	0.1	0.01	0.2	0.02
Grant	6.0	n/a	91,723	1.7	0.3	6.6	0.6	12.9	0.8
Grays Harbor	4.0	n/a	71,692	0.7	0.2	2.9	0.4	5.7	0.7
Island	n/a	n/a	79,177	0.8	0.2	3.1	0.5	6.1	0.7
Jefferson	5.0	n/a	29,854	0.4	0.1	1.4	0.2	2.8	0.3
King	8.9	35.6	2,007,440	62.7	22.7	248.2	45.3	489.0	67.8
Kitsap	6.5	n/a	254,991	5.6	0.8	22.1	1.6	43.5	2.3
Klickitat	5.7	n/a	20,699	0.4	0.1	1.5	0.1	2.9	0.2
Kittitas	7.9	n/a	41,672	1.4	0.1	5.6	0.3	10.6	0.4
Lewis	5.6	n/a	75,621	1.1	0.2	4.5	0.5	8.8	0.7
Lincoln	n/a	n/a	10,437	0.1	0.03	0.4	0.1	0.8	0.1
Mason	7.3	n/a	60,832	1.5	0.2	5.8	0.4	11.4	0.6
Okanogan	9.4	n/a	41,275	1.6	0.1	6.5	0.3	12.6	0.4
Pacific	n/a	n/a	20,575	0.2	0.1	0.8	0.1	1.6	0.2
Pend Oreille	4.2	n/a	12,980	0.2	0.04	0.6	0.1	1.2	0.1
Pierce	7.7	40.3	811,681	24.2	11.7	95.0	23.4	185.4	35.1
San Juan	n/a	n/a	15,824	0.2	0.05	0.6	0.1	1.2	0.1
Skagit	4.4	28.1	118,222	1.2	0.4	4.6	0.7	9.1	1.1
Skamania	n/a	n/a	11,187	0.1	0.03	0.4	0.1	0.9	0.1
Snohomish	7.2	n/a	733,036	20.2	2.2	79.3	4.5	155.1	6.7
Spokane	8.4	43.7	475,735	13.9	9.7	54.8	19.3	107.8	29.0
Stevens	8.8	n/a	43,538	1.5	0.1	6.1	0.3	12.0	0.4
Thurston	5.8	34.9	258,332	5.1	2.2	20.0	4.4	39.3	6.6
Wahkiakum	n/a	n/a	3993	0.04	0.01	0.2	0.02	0.3	0.04
Walla Walla	5.9	n/a	59,404	1.1	0.2	4.4	0.4	8.6	0.5
Whatcom	5.2	30.4	205,262	2.6	0.6	10.5	1.3	20.7	1.9
Whitman	5.5	n/a	46,606	0.8	0.1	3.0	0.3	5.8	0.4
Yakima	9.0	n/a	246,977	9.8	0.8	38.2	1.5	74.4	2.3
Total	–	–	**6,897,012**	**183**	**59**	**722**	**117**	**1,416**	**176**
Total $PM_{2.5}$ + O_3				**242**		**839**		**1,592**	

morbidity cost of air pollution (mainly chronic illness from exposure to particulate matter) might be 25%–30% of the mortality costs. Delucchi and McCubbin [7] summarize studies that indicate that the cost of visibility and agriculture damages from motor-vehicle air pollution in the U.S. is at least 15% of the cost of health damages (including morbidity damages) from motor-vehicle air pollution. Thus, the total cost of air pollution, including morbidity and non-health damages, is at least ~\$8.2 million/mortality, and probably over \$10 million/mortality. In 2050, the cost of life plus morbidity and environmental impacts is expected to grow compared with today, even in 2013 dollars, to \$13.1 (7.3–23.0) million/mortality.

Given this information, the total social cost due to air pollution mortality, morbidity, lost productivity, and visibility degradation in Washington State in 2050 is estimated from the 832 (194–1949) premature mortalities/yr in 2050 to be \$10.9 (1.4–44.9) billion/yr in 2013 dollars (Table 7). Eliminating these costs translates to a \$949 (124–3910)/person/yr savings (Table 7).

Table 7
Avoided air pollution $PM_{2.5}$ plus O_3 premature mortalities in Washington State in 2010–2012 (from Table 6) and 2050 (as described in the spreadsheets of Ref. [8] due to converting to WWS and mean avoided costs and costs per person from mortalities and morbidities in 2050.

	Low	Mean	High
2010–2012 Avoided mortalities/yr	242	839	1592
2050 Avoided mortalities/yr	194	832	1949
2050 Avoided costs (\$2013-bil./yr)	1.42	10.9	44.9
2050 Cost savings (\$2013/person/yr)	124	949	3910

Assumes 2050 population of Washington State of 11,472,193.

8.2. *Global-warming damage costs eliminated by 100% WWS in Washington State*

Table 8 provides an estimate of the change in damages to the U.S. and world, respectively due to converting Washington State's emissions alone to WWS. This estimates account for the state's estimated current and future carbon dioxide emissions and recent estimates of the 2050 social cost of carbon [\$500 (282–1063)/metric tonne-CO_2e in 2013 dollars; [8]]. Damage costs due to climate change include coastal flood and real estate damage costs, agricultural loss costs, energy-sector costs, water costs, health costs due to heat stress and heat stroke, influenza and malaria costs, famine costs, ocean acidification costs, and increased air pollution

Table 8
2050 avoided cost damages to the U.S. and the world due to converting Washington State to 100% WWS. The spreadsheet calculations are provided in Ref. [8].

	Low	Mean	High
Avoided cost ($bil/yr) to U.S. by converting state to WWS	1.4	3.9	10.2
Avoided cost ($bil/yr) to world by converting state to WWS	27.1	48.1	102.4
Avoided cost ($/person/yr) to world by converting state to WWS	2362	4195	8926

Assumes 2050 population of Washington State of 11,472,193.

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. Table 8 indicates that reducing Washington State's own emissions by converting to WWS should benefit both the U.S. and world as a whole.

9. Impacts of WWS on jobs and earnings in the electric power sector

Table 9 provides estimates of the number of jobs and earnings created by implementing WWS-based electricity and the number of 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 analytical complexity required and greater uncertainty as to where those jobs will be located.

Changes in jobs and total earnings are estimated here first with the Jobs and Economic Development Impact (JEDI) models [35]. 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 h of work per year). We assume for this calculation that during each year from 2010 to 2050, 1/40th of the WWS infrastructure is built.

Table 10 provides estimates of the number of Washington State 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. The table footnote describes how the job loss numbers are calculated.

This analysis predicts the creation of ~38,200 40-year construction jobs and 24,900 40-year operation and maintenance jobs, thus a total of 63,100 40-year jobs, for implementing the WWS generators proposed. The shift to WWS will simultaneously result in the loss of ~67,600 jobs in oil, gas, and uranium mining and production; petroleum refining; coal, gas, and nuclear power plant operation; and fuel transportation industries in Washington State. Thus, a net of ~4500 40-year jobs may be lost in Washington State in the electric power sector although such jobs will likely be made up in the manufacture and service of storage technologies, hydrogen technologies, electric vehicles, electric heating and cooling appliances, and industrial heating equipment. The direct and indirect earnings from WWS for the electric power generators amount to $2.2 billion/year during construction and $1.7 billion/yr during operation. The annual earnings lost from fossil-fuel industries (at $69,930 per job) total ~$4.73 billion/yr, giving 40-year construction plus operation earnings minus lost earnings upon converting to WWS for the electric power generation alone of ~ −$814 million/yr. Such losses will likely be made up in other sectors, as discussed above.

10. State tax revenue consideration

The implementation of this plan will likely affect Washington State's tax revenue and may require tax policy changes to ensure that state revenues remain constant.

Revenues directly associated with the sale of petroleum fuels,

Table 9
Summary of job creation and loss and earnings during the construction and operation phases of the WWS electric power infrastructure development, assuming the new installed capacities derived from Table 2.

	New nameplate capacity (MW)	Construction period		Operation period	
		40-yr-Jobs[a]	Earnings (million $/yr)	40-yr Jobs[b]	Earnings (million $/yr)
Onshore wind	38,122	3812	253	5595	496
Offshore wind	10,608	1719	131	6388	441
Wave device	733	239	17	1696	119
Geothermal plant	242	53	3	40	4
Hydropower plant	0	0	0	0	0
Tidal turbine	387	111	8	859	60
Res. roof PV	6766	9293	504	2977	180
Com/gov/roof PV	3137	4420	249	989	61
Utility PV plant	18,077	14,633	791	5092	308
Solar thermal	4404	3943	213	1287	78
Total WWS	82,476	38,223	2169	24,923	1747
Job or earnings loss				67,603	$4730
Net 40-y gains WWS				**−4457**	**−$814**

[a] 40-year jobs are the number of full-time equivalent (FTE) 1-year (2080 h of work per year) jobs for 40 years.

[b] 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
Job loss in Washington State upon eliminating energy generation from the fossil fuel and nuclear sectors in the state.

Energy sector	Number of jobs lost
Oil and gas extraction/production	3,819[a]
Petroleum refining	2,552[b]
Coal/gas power plant operation	3,882[c]
Uranium mining	84[d]
Nuclear power plant operation	1,100[e]
Coal and oil transportation	54,102[f]
Other*	3,791[g]
Less petroleum jobs retained	1,727[h]
Total	67,603

[a] [16].

[b] Workers employed in U.S. refineries from Ref. [13] multiplied by fraction of U.S. barrels of crude oil distilled in Washington State from Ref. [14].

[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. [41]. All other data from Ref. [36].

[d] Product of U.S. uranium mining employment across 12 U.S. states that mine uranium from Ref. [15] and the fraction of Washington State population in those 12 states.

[e] [33].

[f] Product of the total number of direct U.S. jobs in transportation (11,000,000) from Ref. [44] and 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. [43] and the fraction of transportation jobs that are relevant to oil and coal transportation (0.78) from Ref. [42] and the fraction of the U.S. population in Washington State.

[g] 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 [37].

[h] Jobs retained are in the production of non-fuel petroleum commodities such as lubricants, asphalt, petrochemical feedstocks, and petroleum coke; calculated as follows: Washington State employs ~3800 workers in oil and gas production and ~2500 workers in oil refineries (Table 10). Nationally, the non-fuel output from oil refineries is ~10% of refinery output [12]. We thus assume that only 10% (~630) of petroleum production and refining jobs will remain upon conversion to WWS. We assume another 1,070 will remain for transporting this petroleum for a total of ~1,700 jobs remaining.

such as the gasoline and diesel fuel taxes, will diminish as the vehicle fleet is made more efficient and ultimately transitions away from petroleum altogether. In 2012, motor fuel taxes accounted for 7.28% of Washington State's total tax revenue, about $1.2 billon [50]. To offset these motor fuel revenue losses, the Washington State legislature enacted RCW 46.17.323, which took effect in February of 2013 and imposes a $100 vehicle registration renewal fee on vehicles propelled solely by electricity. With over 6 million passenger cars and light trucks in operation in the state in 2012, revenue generated through this registration fee once an electric fleet is developed would account for half of the lost revenue, $600 million. Other tax revenues associated with passenger vehicle use, such as motor vehicle fees, taxi surcharge fees, and auto rental taxes, are not expected to decrease significantly upon conversion to WWS.

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

11. Timeline of implementation of the plan

Fig. 4 shows one possible timeline scenario for the implementation of this roadmap in Washington State. The plan proposes 80–85% conversion to WWS by 2030 and 100% by 2050. For such a timeline to be met, we propose that, by 2020, all new power plants and heating/cooling, drying, and cooking in the residential and commercial sectors should be WWS; by 2020–2025, all new large-scale water-borne freight transfer should be WWS; by 2025, all new rail and bus transport should be WWS; by 2025–2030, all new off-road transport, small-scale marine, light-duty on-road transport, heavy-duty truck transport, and industrial processes should be WWS; by 2035, all new short-haul aircraft should be WWS; and by 2040, all new long-haul aircraft should be WWS.

12. Recommended first steps

In order to meet the proposed timeline in Fig. 4, significant policy measures are needed. Here, some policy options are listed to help with this goal.

12.1. State planning and incentives

- Create a green building tax credit program for the corporate sector.
- Create energy performance rating systems with minimum performance requirements to assess energy efficiency levels across the state and pinpoint areas for improvement.
- Lock in the remaining in-state coal-fired power plants to retire under enforceable commitments. At the same time, streamline the permit approval process for WWS power generators and high-capacity transmission lines.
- Within existing regional planning efforts, work with local and regional governments to manage zoning and permitting issues or pre-approve sites to reduce the costs and uncertainty of projects and expedite their physical build-out. In the case of offshore wind, include the federal government in planning and management efforts.

12.2. Energy efficiency

- Conservation Initiative No. 937 calls for 17 out of Washington's 62 electric utilities, representing 84% of Washington State's load, to undertake all cost effective energy conservation measures. These standards can be expanded to the remaining 16% of the utilities sector and to the industrial and commercial sectors.
- Introduce a Public Benefit Funds (PBF) program for energy efficiency. The program is funded with a non-bypassable charge on consumers' electricity bills for distribution services. These funds generate capital that sponsor energy efficiency programs, and research and development related to clean energy technologies and training.
- Promote, though municipal financing, incentives, and rebates, energy efficiency measures in buildings. Efficiency measures include, but are not limited to, using LED lighting; optimized air conditioning systems; evaporative cooling; ductless air conditioning; water-cooled heat exchangers; night ventilation cooling; heat-pump water heaters; improved data center design; improved air flow management; advanced lighting controls; combined space and water heaters; variable refrigerant flow; and improved wall, floor, ceiling, and pipe insulation. Other measures include sealing leaks in windows, doors, and fireplaces, converting to double-paned windows, using more passive solar heating, monitoring building energy use to determine wasteful processes, and performing energy audits to discover energy waste.
- Continuously revise building codes for construction of new buildings and renovation of existing buildings as new technologies become readily available.

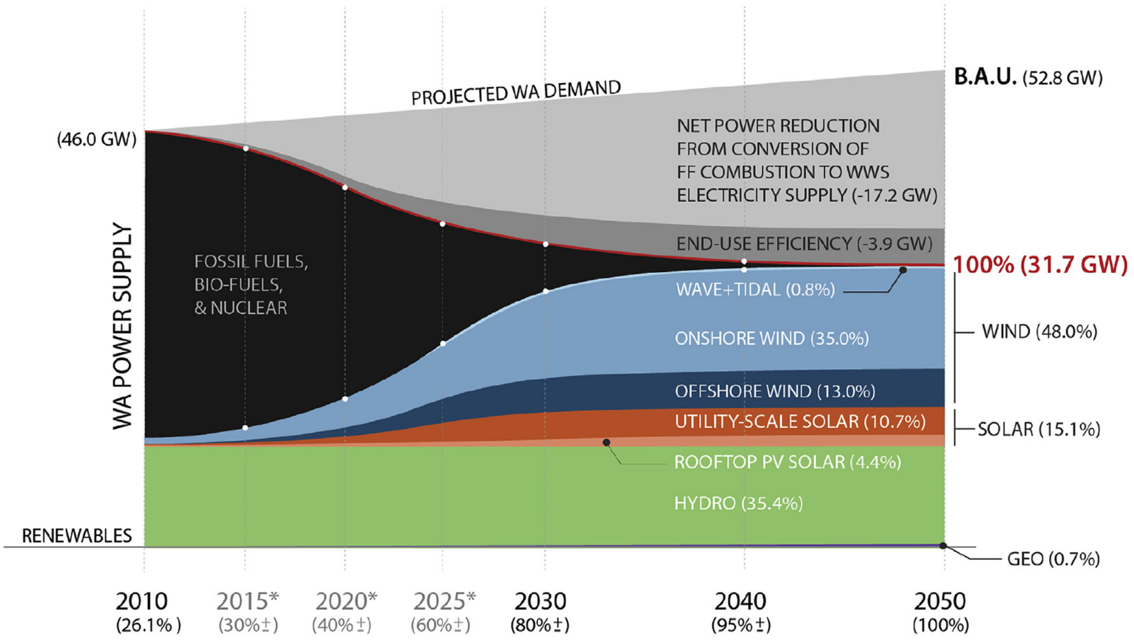

Fig. 4. Change in Washington State end-use all-purpose (electricity, transportation, heating/cooling, and industry) supply and demand over time with business as usual (BAU) versus WWS. Total power demand decreases upon conversion to WWS due to the efficiency of electricity over combustion and end-use energy efficiency measures. 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. The numbers in parentheses are values in 2050. The percent conversions assumed in the figure are 30% by 2015, 40% by 2020, 80% by 2030, 95% by 2040, and 100% by 2050. Karl Burkart (personal communication).

- Incentivize landlords' investment in efficiency. Allow owners of multi-family buildings to take a property tax-exemption for energy efficiency improvements made in their buildings that provide benefits to their tenants.
- Create a rebate program that targets energy efficiency in appliances and processes. Examples of efficiency measures include upgrading appliances to those that use less electricity, using hot water circulation pumps on a timer, and converting to LED light bulbs.
- Encourage conversion from natural gas water and air heaters to heat pumps (air and ground-source) and rooftop solar thermal hot water pre-heaters. Incentivize more use of efficient lighting in buildings and on city streets. Publicize ground source heat pumps as a key energy efficiency technology for Washington by retrofitting a high-profile state building.
- Have the top five retailers of electricity in Washington State devise a specific rate schedule to account for a ground source heat pump's constant low-level usage of electricity.

12.3. *Energy supply*

- Increase Washington State's Renewable Portfolio Standards (RPS). The current 15% RPS sunsets in 2020. Ramp up the RPS to get to 80% by 2030 and 100% by 2050.
- Extend the state solar production tax credit.
- Encourage the progression toward WWS by implementing a tax on emissions by current utilities.
- Streamline the small-scale solar and wind installation permitting process. Create common codes, fee structures, and filing procedures across the state.
- Encourage clean-energy backup emergency power systems rather than diesel/gasoline generators at both the household and community levels. Work with industry to implement home or community energy storage (through battery systems, including re-purposed BEV batteries) accompanying rooftop solar to mitigate problems associated with grid power losses.

12.4. *Utilities*

- Implement virtual net metering (VNM) for small-scale energy systems. To that end, remove the necessity for subscribers to have proprietorship in the energy-generating site. Expand or eliminate the capacity limit of net metering for each utility, and remove the barrier to inter-load zone transmission of net-metered renewable power.
- Develop peak-load management strategies to account for the variability of renewable energy integration to the grid as California did recently by setting a goal to install 1.3 GWh of grid storage by 2020.
- Encourage utilities to use demand-response grid management to reduce the need for short-term energy backup on the grid.

12.5. *Transportation*

- Create a governor-appointed EV Advisory Council, as has been done in Illinois and Connecticut, to recommend strategies for EV infrastructure and policies.
- Leverage and augment the technical and financial assistance of the U. S. Department of Energy's "Clean Cities Program" activities, focusing on the deployment of BEVs.
- Adopt legislation mandating the transition to plug-in electric vehicles for short- and medium distance government transportation and encouraging the transition for commercial and personal vehicles through purchase incentives and rebates.
- Use incentives or mandates to stimulate the growth of fleets of electric and/or hydrogen fuel cell/electric hybrid buses starting with a few and gradually growing the fleets. Electric or hydrogen fuel cell ferries, riverboats, and other local shipping should be encouraged as well.

- Encourage and ease the permitting process for the installation of electric charging stations in public parking lots, hotels, suburban metro stations, on streets, and in residential and commercial garages.
- Set up time-of-use electricity rates to encourage charging at night.
- Use excess wind and solar produced by WWS electric power generators to produce hydrogen (by electrolysis) for transportation and industry and to provide district heat for water and air instead of curtailing the wind and solar.
- Encourage the electrification of freight rail and shift freight from trucks to rail.
- Encourage more use of public transit by increasing availability and providing incentives. Successful programs have been seen on college or university campuses in which commuters receive compensation for not purchasing a parking pass and opting to use public transportation or personal bicycles for their commute.
- Increase safe biking and walking infrastructure, such as dedicated bike lanes, sidewalks, crosswalks, timed walk signals, etc.

12.6. Industrial processes

- Provide tax or other financial incentives for industry to convert to electricity and electrolytic hydrogen for high temperature and manufacturing processes where they are not currently used.
- Provide tax or other financial incentives to encourage industries to use WWS electric power generation for on-site electric power (private) generation.

13. Summary

This study analyzes the technical and economic feasibility of a roadmap for converting Washington State's energy infrastructure for all purposes to a clean and sustainable one powered by wind, water, and sunlight (WWS) producing electricity and hydrogen. The roadmap calls for 80–85% replacement of the current infrastructure with WWS by 2030 and 100% replacement by 2050. The conversion from combustion to electricity for all purposes will reduce Washington State's end-use power demand ~39.9% and stabilize energy prices since fuel costs will be zero. About 20% of this reduction is due to end-use energy efficiency measures, some is due to eliminating the mining, transport, and refining of coal, oil, gas, and uranium, and the rest is due to the efficiency of electricity over combustion Remaining 2050. all-purpose end-use Washington State power demand is proposed to be met with 7624 new onshore 5-MW wind turbines (with new plus existing onshore wind providing 35% of Washington State's all-purpose energy), 2122 offshore 5-MW wind turbines (13%), 372 50-MW solar-PV power plants (10.73%), 1.35 million 5-kW residential rooftop PV systems (2.9%), 31,400 100-kW commercial/government rooftop systems (1.5%), 2.4 100-MW geothermal plants (0.65%), 977 0.75-MW wave devices (0.5%), 387 1-MW tidal turbines (0.3%), but no new hydropower plants. Existing hydropower plants would supply 35.42% of 2050 all-purpose end-use power. This is just one plausible mix.

The additional footprint on land for WWS devices is equivalent to about 0.08% of Washington State's land area, mostly for utility scale PV. An additional on-land spacing area of about 1.97% is required for onshore wind, but this area can be used for multiple purposes, such as open space, agricultural land, or grazing land.

By 2050, conversion to 100% WWS may allow each person in Washington State to save ~$85/person/yr in direct energy costs and $950/person/yr in health costs while reducing another $4200/person/yr in global climate costs. Health cost savings arise because the plan will reduce ~830 (190–1950) premature air pollution mortalities/yr in Washington State in 2050, saving the state $10.9 (1.4–45) billion/yr in 2050 health costs (2013 dollars). Further, the state's own emission decreases will reduce 2050 global-warming costs by at least another $48 (27–102) billion/yr. 2050 health and climate cost savings alone will repay the $163.7 billion capital cost for the 82.5 GW in new installed capacity needed within ~3 years.

The plan is anticipated to create ~38,200 40-year construction jobs and 24,900 40-year operation and maintenance jobs for new electric-power generating facilities alone while causing 67,600 job losses in the fossil-fuel and nuclear industries. This will result in net 40-year job loss of ~4500 jobs in the electric power sector although such jobs will likely be made up in the manufacture and service of storage technologies, hydrogen technologies, electric vehicles, electric heating and cooling appliances, and industrial heating equipment.

This study provides estimates that have uncertainties, many of which are captured in broad ranges of energy, health, and climate costs given. However, these ranges may not capture cost changes due to limits on WWS supply caused by wars and other conflicts, political or social opposition to the roadmaps, or other unforeseen circumstances. As such, our estimates should be updated frequently between now and 2050. Nevertheless, it is expected that the implementation of plans such as this in countries worldwide will eliminate energy-related global warming; air, soil, and water pollution; and energy insecurity.

Acknowledgments

We would like to thank Elaine Hart, Anthony R. Ingraffea, Robert W. Howarth, Karl Burkart, Jon Wank, Mark Ruffalo, Marco Krapels, and Josh Fox for helpful comments and insight and The Solutions Project for partial student funding. The spreadsheets and links to infographics for this paper can be found in [6].

References

[1] A.L.F. Braga, A. Zanobetti, J. Schwartz, Do respiratory epidemics confound the association between air pollution and daily deaths, Eur. Respir. J. 16 (2000) 723–728.

[2] S. Becker, B.A. Frew, G.B. Andresen, T. Zeyer, S. Schramm, M. Greiner, M.Z. Jacobson, Features of a fully renewable U.S. electricity-system: optimized mixes of wind and solar PV and transmission grid extensions, Energy 72 (2014) 443–458.

[3] C.D. Budischak, D. Sewell, H. Thomson, L. Mach, D.E. Veron, W. Kempton, Cost-minimized combinations of wind power, solar power, and electrochemical storage, powering the grid up to 99.9% of the time, J. Power Sources 225 (2013) 60–74.

[4] CARB (California Air Resources Board), Estimate of Premature Deaths Associated with Fine Particle Pollution (PM2.5) in California Using a U.S. Environmental Protection Agency Methodology Air Quality Data Query Tool, 2012. http://www.arb.ca.gov/aqmis2/aqdselect.php (accessed 08.07.12).

[5] D. Connolly, H. Lund, B.V. Mathiesen, M. Leahy, The first step towards a 100% renewable energy-system for Ireland, Appl. Energy 88 (2011) 502–507.

[6] M.A. Delucchi, M.Z. Jacobson, Providing all global energy with wind, water, and solar power, part II: reliability, system and transmission costs, and policies, Energy Policy 39 (2011) 1170–1190.

[7] M.A. Delucchi, D.M. McCubbin, External costs of transport in the united states, in: A. de Palma, R. Lindsey, E. Quinet, R. Vickerman (Eds.), Chapter 15 of a Handbook in Transport Economics, Edward Elgar Publishing, Cheltenham, U.K, 2011, pp. 341–368.

[8] M.A. Delucchi, M.Z. Jacobson, G. Bazouin, Z.A.F. Bauer, Spreadsheets for 50-state 100% Wind, Water, and Solar Roadmaps, 2015. http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html (accessed 05.04.15).

[9] DOE (Department of Energy), Installed Wind Capacity, 2014. http://www.windpoweringamerica.gov/wind_installed_capacity.asp (accessed 04.06.14).

[10] M. Dvorak, C.L. Archer, M.Z. Jacobson, California offshore wind energy potential, Renew. Energy 35 (2010) 1244–1254.

[11] EIA (Energy Information Administration, U.S.), State Renewable Electricity Profiles 2010, 2012. http://www.eia.gov/renewable/state/ (accessed 21.06.14).

[12] EIA (Energy Information Administration, U.S.), Petroleum and Other Liquids.

U.S. Supply, Disposition, and Ending Stocks of Crude Oil and Petroleum Products, 2013. http://www.eia.gov/petroleum/supply/annual/volume1/ (accessed 27.10.13).

[13] EIA (Energy Information Administration), Annual Energy Outlook, 2014. http://www.eia.gov/forecasts/aeo/tables_ref.cfm (accessed 21.06.14).

[14] EIA (Energy Information Administration), Number and Capacity of Operable Petroleum Refineries by PAD District and State as of January 1, 2013, 2014. http://www.eia.gov/petroleum/refinerycapacity/table1.pdf (accessed 14.07.14).

[15] EIA (Energy Information Administration), Domestic Uranium Production Report – Annual, 2014. http://www.eia.gov/uranium/production/annual/ (accessed 21.06.14).

[16] EMSI, A Broader Look at America's Natural Gas Boom, 2012. http://www.economicmodeling.com/2012/03/16/a-broader-look-at-americas-fossil-fuels-jobs-boom/ (accessed 21.06.14).

[17] EPRI (Electric Power Research Institute), Mapping and Assessment of U.S. Wave Energy Resource, 2011. Technical Report 2011, http://en.openei.org/datasets/files/884/pub/mapping_and_assessment_of_the_us_ocean_wave_energy_resource.pdf (accessed 16.12.13).

[18] D.J. Fleischmann, An Assessment of Geothermal Resource Development Needs in the Western United States, 2007. http://www.geo-energy.org/reports/States%20Guide.pdf (accessed 15.12.13).

[19] E.K. Hart, M.Z. Jacobson, A Monte Carlo approach to generator portfolio planning and carbon emissions assessments of systems with large penetrations of variable renewables, Renew. Energy 36 (2011) 2278–2286.

[20] M.Z. Jacobson, Review of solutions to global warming, air pollution, and energy security, Energy Environ. Sci. 2 (2009) 148–173.

[21] M.Z. Jacobson, Enhancement of local air pollution by urban CO_2 domes, Environ. Sci. Technol. 44 (2010) 2497–2502.

[22] M.Z. Jacobson, W.G. Colella, D.M. Golden, Cleaning the air and improving health with hydrogen fuel cell vehicles, Science 308 (2005) 1901–1905.

[23] M.Z. Jacobson, M.A. Delucchi, A Path to Sustainable Energy by 2030, Scientific American, November 2009.

[24] M.Z. Jacobson, M.A. Delucchi, Providing all global energy with wind, water, and solar power, part I: technologies, energy resources, quantities and areas of infrastructure, and materials, Energy Policy 39 (2011) 1154–1169.

[25] M.Z. Jacobson, R.W. Howarth, M.A. Delucchi, S.R. Scobies, J.M. Barth, M.J. Dvorak, M. Klevze, H. Katkhuda, B. Miranda, N.A. Chowdhury, R. Jones, L. Plano, A.R. Ingraffea, Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight, Energy Policy 57 (2013) 585–601.

[26] M.Z. Jacobson, M.A. Delucchi, A.R. Ingraffea, R.W. Howarth, G. Bazouin, B. Bridgeland, K. Burkhart, M. Chang, N. Chowdhury, R. Cook, G. Escher, M. Galka, L. Han, C. Heavey, A. Hernandez, D.F. Jacobson, D.S. Jacobson, B. Miranda, G. Novotny, M. Pellat, P. Quach, A. Romano, D. Stewart, L. Vogel, S. Wang, H. Wang, L. Willman, T. Yeskoo, A roadmap for repowering California for all purposes with wind, water, and sunlight, Energy 73 (2014) 875–889.

[27] M.Z. Jacobson, M.A. Delucchi, M.A. Cameron, B.A. Frew, A low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes, Proc. Nat. Acad. Sci. (2015) in press.

[28] J. Lepeule, F. Laden, D. Dockery, J. Schwartz, Chronic exposure to fine particles and mortality: an extended follow-up of the Harvard six cities study from 1974 to 2009, Environ. Health Perspect. 120 (2012) 965–970.

[29] J.I. Levy, J.J. Buonocore, K. von Stackelberg, Evaluation of the public health impacts of traffic congestion: a health risk assessment, Environ. Health 9 (2010), http://dx.doi.org/10.1186/1476-069X-9-65.

[30] T. Mai, et al., Renewable electricity futures for the United States, IEEE Trans. Sustain. Energy 5 (2014) 372–378.

[31] B.V. Mathiesen, H. Lund, K. Karlsson, 100% Renewable energy systems, climate mitigation and economic growth, Appl. Energy 88 (2011) 488–501.

[32] D.R. McCubbin, M.A. Delucchi, The health costs of motor-vehicle related air pollution, J. Transp. Econ. Policy 33 (1999) 253–286.

[33] NEI (Nuclear Energy Institute), Nuclear Statistics, 2014. http://www.nei.org/Knowledge-Center/Map-of-US-Nuclear-Plants (accessed 21.06.14).

[34] NREL (National Renewable Energy Laboratory), Geothermal Technologies Program, Washington, 2005. http://www.nrel.gov/docs/fy05osti/36549.pdf (accessed 15.12.13).

[35] NREL (National Renewable Energy Laboratory), Jobs and Economic Development Impact Models (JEDI), 2013. http://www.nrel.gov/analysis/jedi/download.html (accessed 27.10.13).

[36] ONET Online, 2014. http://www.onetonline.org/ (accessed 21.06.13).

[37] Petrostrategies, Inc, People Who Work in the Oil and Gas Industry, 2014. http://www.petrostrategies.org/Learning_Center/people_who_work_in_the_oil_and_gas_industry.htm (accessed 21.06.14).

[38] C.A. Pope III, R.T. Burnett, M.J. Thun, E.E. Calle, D. Krewski, K. Ito, G.D. Thurston, Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, J. Amer. Med. Assoc. 287 (2002) 1132–1141.

[39] Renewable Northwest Project, Solar Energy Project, 2013. http://www.rnp.org/node/solar-energy-technology (accessed 16.12.13).

[40] H.A. Roman, J.K. Hammitt, T.L. Walsh, D.M. Stieb, Expert elicitation of the value per statistical life in an air pollution context, Risk Anal. 32 (2012) 2133–2151.

[41] Sourcewatch, Coal and Jobs in the United States, 2014. http://www.sourcewatch.org/index.php?title=Coal_and_jobs_in_the_United_States (accessed 21.06.14).

[42] USBLS (U.S. Bureau of Labor Statistics), Occupational Employment Statistics, 2014. http://www.bls.gov/oes/current/oes_nat.htm#53-0000 (accessed 21.06.14).

[43] USDOT (U.S. Department of Transportation), Commodity Flow Survey, 2012. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/commodity_flow_survey/brochure_2012.html (accessed 21.06.14).

[44] USDOT (U.S. Department of Transportation), Growth in the Nation's Freight Shipments, 2014. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/freight_shipments_in_america/html/entire.html (accessed 21.06.14).

[45] USEPA (U.S. Environmental Protection Agency), National Ambient Air Quality Standards for Particulate Pollution, 2006. Washington, D.C.

[46] USEPA (U.S. Environmental Protection Agency), Benefits and Costs of the Clean Air Act, Second Prospective Study – 1990 to 2020, 2011. http://www.epa.gov/air/sect812/feb11/benefitsfullreport.pdf. http://www.epa.gov/air/sect812/prospective2.html (accessed 23.11.11).

[47] USGS (U.S. Geological Survey), Assessment of Moderate – and High-temperature Geothermal Resources in the United States, 2008. http://pubs.usgs.gov/fs/2008/3082/pdf/fs2008-3082.pdf (accessed 16.12.13).

[48] Washington State Department of Commerce, Energy Strategy and Biennial Energy Reports, 2014. http://www.commerce.wa.gov/Programs/Energy/Office/Topics/Pages/EnergyStrategy.aspx (accessed 13.07.13).

[49] Washington State Department of Ecology, Washington State Annual Average Solar Resource Potential, 2007. http://www.ecy.wa.gov/climatechange/maps/solar/solar_state.pdf (accessed 15.12.13).

[50] Washington State Department of Revenue. http://dor.wa.gov/Content/Home/Default.aspx, 2013 (accessed 16.12.13).