A roadmap for repowering California for all purposes with wind, water, and sunlight

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ABSTRACT

This study presents a roadmap for converting California's all-purpose (electricity, transportation, heating/cooling, and industry) energy infrastructure to one derived entirely from wind, water, and sunlight (WWS) generating electricity and electrolytic hydrogen. California's available WWS resources are first evaluated. A mix of WWS generators is then proposed to match projected 2050 electric power demand after all sectors have been electrified. The plan contemplates all *new* energy from WWS by 2020, 80–85% of existing energy converted by 2030, and 100% by 2050. Electrification plus modest efficiency measures may reduce California's end-use power demand ~44% and stabilize energy prices since WWS fuel costs are zero. Several methods discussed should help generation to match demand. A complete conversion in California by 2050 is estimated to create ~220,000 more 40-year jobs than lost, eliminate ~12,500 (3800–23,200) state air-pollution premature mortalities/yr, avoid $103 (31–232) billion/yr in health costs, representing 4.9 (1.5–11.2)% of California's 2012 gross domestic product, and reduce California's 2050 global climate cost contribution by $48 billion/yr. The California air-pollution health plus global climate cost benefits from eliminating California emissions could equal the $1.1 trillion installation cost of 603 GW of new power needed for a 100% all-purpose WWS system within ~7 (4–14) years.

1. Introduction

This paper presents a roadmap for converting California's energy infrastructure in all sectors to one powered by wind, water, and sunlight (WWS). The California plan is similar in outline to one recently developed for New York State [39], but expands, deepens, and adapts the analysis for California in several important ways.

The estimates of energy demand and potential supply are developed specifically for California, which has a higher population, faster population growth, greater total energy use, and larger transportation share of total energy, but lower energy-use per capita, than does New York. The California analysis also includes originally-derived (1) computer-simulated resource analyses for both wind and solar, (2) calculations of current and future rooftop and parking structure areas and resulting maximum photovoltaic (PV) capacities for 2050, (3) air-pollution mortality calculations considering three years of hourly data at all air quality monitoring stations in the state, (4) estimates of cost reductions associated

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with avoided air-pollution mortality and morbidity, (5) potential job creation versus loss numbers, (6) estimates of the future cost of energy and of avoided global-warming costs, and (7) WWS supply figures based on 2050 rather than 2030 energy demand along with a more detailed discussion of energy efficiency measures. It further provides a transition timeline and develops California-relevant policy measures. The California plan as well as the prior New York plan build on world and U.S. plans developed by Jacobson and Delucchi [37,38] and Delucchi and Jacobson [12]. Neither the California plan nor the prior New York plan is an optimization study; that is, neither attempts to find the least-cost future mix of generation technologies, demand-management strategies, transmission systems, and storage systems that satisfies reliability constraints. However, this study does discuss results from such an optimization analysis based on contemporary California energy demand.

Several partial renewable-energy plans for California have been proposed previously. For example, California has a renewable portfolio standard (RPS) requiring 33% of its electric power to come from renewable sources by 2020. Williams et al. [77] hypothesized the infrastructure and technology changes need to reduce California emissions 80% by 2050. Wei et al. [76] used detailed projections of energy demand and a high-resolution resource capacity planning model to evaluate supply and demand alternatives that could reduce greenhouse-gas emissions in California 80% below 1990 levels by 2050. Although these efforts are insightful and important, the plan proposed here goes farther by analyzing a long-term sustainable energy infrastructure that supplies 100% of energy in *all* sectors (electricity, transportation, heating/cooling, and industry) from wind, water, and solar power (without fossil fuels, biofuels, or nuclear power), and hence provides the largest possible reductions in air pollution, water pollution, and global-warming impacts. In addition, unlike the other California studies, the present study quantifies air-pollution mortality and reduced costs due to reduced mortality and climate damage upon a conversion, along with job creation minus loss numbers. Further, it quantifies and differentiates between footprint and spacing areas required for the energy technologies and provides in-depth first-step policy measures for a conversion.

2. How the technologies were chosen?

The WWS energy technologies chosen for California are existing technologies ranked the highest among several proposed energy options for addressing pollution, public health, global warming, and energy security [35]. That ranking study concluded that, for electricity; wind, concentrated solar, geothermal, solar PV, tidal, wave, and hydroelectric power (WWS) were the best overall options. For transportation, battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (HFCVs), where the hydrogen is produced by electrolysis from WWS electricity, were the ideal options. Long-distance transportation would be powered by BEVs with fast charging or battery swapping (e.g., Ref.[50]). Heavy-duty transportation would include BEV-HFCV hybrids. Heating/cooling would be powered primarily by electric heat pumps. High-temperature industrial processes would be powered by electricity and combusted electrolytic hydrogen. Hydrogen fuel cells would be used only for transportation, not for electric power generation due to the inefficiency of that application for HFCVs. Although electrolytic hydrogen for transportation is less efficient and more costly than is electricity for BEVs, there are some segments of transportation where hydrogen-energy storage may be preferred over battery-energy storage (e.g., ships, aircraft, long-distance freight). Jacobson and Delucchi [38] and Jacobson et al. [39] explain why this energy plan does not include nuclear power, coal with carbon capture, liquid or solid biofuels, or natural gas. However, this plan does include energy efficiency measures.

3. Change in California power demand upon conversion to WWS

Table 1 summarizes global, U.S., and California end-use power demand in 2010 and 2050 upon a conversion to a 100% WWS infrastructure (zero fossil fuel, biofuel, or nuclear energy). The table was derived from a spreadsheet available in Ref. [40] using annually averaged end-use power demand data and the same methodology as in Ref. [38]. All end uses that feasibly can be electrified are assumed to use WWS power directly, and remaining end uses are assumed to use WWS power indirectly in the form of electrolytic hydrogen. Some transportation would include HFCVs, and some high-temperature industrial heating would include hydrogen combustion. Hydrogen would not be used for electricity generation due to its inefficiency in that capacity. In this plan, electricity requirements increase because all energy sectors are electrified, but the use of oil and gas for transportation and heating/cooling decreases to zero. The increase in electricity use is much smaller than the decrease in energy embodied in gas, liquid, and solid fuels because of the high efficiency of electricity for heating and electric motors. As a result, end-use power demand decreases significantly in a WWS world (Table 1).

The 2010 power required to satisfy all end-use power demand worldwide for all purposes was ~12.5 trillion watts (terawatts, TW). Delivered electricity was ~2.2 TW of this. End-use power excludes losses incurred during production and transmission of the power. If the use of conventional energy, mainly fossil fuels, grows as projected in Table 1, all-purpose end-use power demand in 2050 will increase to ~21.6 TW for the world, ~3.08 TW for the U.S., and ~280 GW for California. Conventional power demand in California is projected to increase proportionately more in 2050 than in the U.S. as a whole because California's population is expected to grow by 35.0% between 2010 and 2050, whereas the U.S. population is expected to grow by 29.5% (Table 1).

Table 1 indicates that a complete conversion by 2050 to WWS could reduce world, U.S., and California end-use power demand and the power required to meet that demand by ~30%, ~38%, and 44%, respectively. About 5–10 percentage points of these reductions (5.6 percentage points in the case of California) are due to modest energy-conservation measures. The EIA [21] growth projections of conventional demand between 2010 and 2050 in Table 2 account for some end-use efficiency improvements as well, so the 5–10 percentage point reductions are on top of those. Table S6 and Section 11 indicate that efficiency measures can reduce energy use in non-transportation sectors by 20–30% or more, which means that our assumption of a 5–10% demand reduction due to energy conservation on top of EIA [21] assumed modest demand reductions in the baseline projection is likely conservative. Thus, if the achieved demand reduction by 2050 exceeds our assumption, then meeting California's energy needs with 100% WWS will be easier to implement than proposed here.

Another relatively small portion of the reductions in Table 1 is due to the fact that conversion to WWS reduces the need for upstream coal, oil, and gas mining and processing of fuels, such as petroleum or uranium refining. The remaining and major reason for the reduction in end-use energy is that the use of electricity for heating and electric motors is more efficient than is fuel combustion for the same applications [38]. Also, the use of WWS electricity to produce hydrogen for fuel cell vehicles, while less efficient than is the use of WWS electricity to run BEVs, is more efficient and cleaner than is burning liquid fossil fuels for vehicles [33,38]. Combusting electrolytic hydrogen is slightly less efficient but

Table 1
Contemporary (2010) and projected (2050) end-use power demand (TW of delivered power) for all purposes by sector, for the world, U.S., and California if conventional fuel use continues as projected or if 100% conversion to WWS occurs.

Energy sector	Conventional fossil fuels and wood 2010 (TW)			Conventional fossil fuels and wood 2050 (TW)			Replacing fossil fuels and wood with WWS 2050 (TW)		
	World	U.S.	CA	World	U.S.	CA	World	U.S.	CA
Residential	1.77	0.39	0.030	3.20	0.49	0.041	2.6	0.41	0.033
Commercial	0.94	0.29	0.024	2.00	0.37	0.032	1.9	0.33	0.030
Industrial	6.40	0.78	0.048	11.2	1.02	0.066	8.9	0.82	0.053
Transportation	*3.36*	*0.92*	*0.103*	*5.3*	*1.20*	*0.141*	*1.7*	*0.37*	*0.042*
Total	12.47	2.37	0.206	21.6	3.08	0.280	15.1	1.92	0.157
Percent change							(−30%)	(−37.6%)	(−43.7)

Source: Spreadsheets to derive the table are given in Ref. [40], who used the method of Jacobson and Delucchi [38] with EIA [21] end-use demand data. U.S (CA) population was 308,745,538 (37,309,382) in 2010 and is projected to be 399,803,000 (50,365,074) in 2050 [70], giving the U.S. (California) 2010−2050 population growth as 29.5% (35.0%).

cleaner than is combusting fossil fuels for direct heating, and this is accounted for in Table 1.

The percentage reduction in California power demand upon conversion to WWS in Table 1 exceeds the reduction in U.S. power demand because the transportation-energy share of the total is greater in California than in the U.S., and efficiency gains from electrifying transportation are greater than are those from electrifying other sectors. The power demand reduction in the U.S. exceeds that worldwide for the same reason.

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

How many WWS power plants or devices are needed to power California for all purposes assuming end-use power requirements in Table 1 and accounting for electrical transmission and distribution losses? Table 2 provides one of several possible future scenarios for 2050. Upon actual implementation, the number of each generator in this mix will likely shift − e.g., perhaps more offshore wind, less onshore wind. Environmental and zoning regulations will govern the siting of facilities. Development in "low-conflict zones," where and biological resource value is low and energy resources are high, will be favored. Some such areas include lands already mechanically, chemically or physically impaired; brown fields; locations in or near urban areas; locations in the built environment; locations near existing transmission and roads; and locations already designated for renewable energy development. Decisions on siting should take into account biodiversity and wildlife protection but should not inhibit the implementation of the roadmap, because such a delay would allow fossil fuel plants to persist and cause greater damage to human and animal life.

Solar and wind are the largest generators of electric power under this plan because they are the only two resources sufficiently available to power California on their own, and both are needed in combination to ensure the reliability of the grid. Lund [47] suggests an optimal ratio of wind-to-solar of 2:1 in the absence of load balancing by hydroelectric or CSP with storage. The present study includes load balancing by both, which makes it reasonable for us to assume larger penetrations of solar (in Table 2) than in that study. In addition, since a 100% WWS world will include more flexible loads than today, such as BEV charging and hydrogen production, it will be possible to shift times of load to match better peak WWS availability. Finally, power in many U.S. states will be dominated by wind (e.g., in Ref. [39], the proposed New York wind-to-solar ratio is 1.5:1 with hydroelectric used for load balancing). California, though, has a larger accessible solar resource than most states, and wind is more limited in terms of where it is available. In sum, the choice of a larger ultimate penetration of solar in

California for 2050 was not based on an optimization study but on practical considerations specific to the state, the load balancing resources available, and the potential for large flexible loads in the state.

Since a portion of wind and all wave and tidal power will be offshore under the plan, some transmission will be under water and out of sight. Transmission for new onshore wind, solar, and geothermal power plants will be along existing pathways but with enhanced lines to the greatest extent possible, minimizing zoning issues as discussed in Section S4.

The footprint area shown in Table 2 is the physical area on top of the ground needed for each energy device (thus does not include underground structures), whereas the 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. Most spacing area can be used for open space, agriculture, grazing, etc. Table 2 indicates that the total new land footprint required for this plan is ~0.90% of California's land area, mostly for solar PV and CSP power plants (as mentioned, rooftop solar does not take up new land). Additional space is also needed between onshore wind turbines. This space can be used for multiple purposes and can be reduced if more offshore wind resources are used than proposed here. Fig. 1 shows the relative footprint and spacing areas required in California.

5. WWS resources available

California has more wind, solar, geothermal, plus hydroelectric resource than is needed to supply the state's energy for all purposes in 2050. Fig. 2a and b shows estimates, at relatively coarse horizontal resolution (0.6° W−E × 0.5° S−N), of California's onshore and offshore annual wind speed and capacity factor, respectively (assuming an RePower 5 MW, 126-m rotor turbine) at 100 m above the topographical surface. They are derived from three-dimensional computer model simulations performed as part of this study. The deliverable power in California at 100 m in locations with capacity factor >30%, before excluding areas where wind cannot readily be developed, is ~220 GW (1930 TWh/yr). This translates to ~713 GW of installed power for this turbine operating in 7−8.5 m/s winds. Assuming two-thirds of the windy areas are not developable gives a technical potential of ~238 GW of installed capacity and 73.3 GW of delivered power. These resources easily exceed the 39.4 GW (345 TWh/yr) of delivered power needed to provide 25% of California's 2050 all-purpose energy demand in a WWS world (Table 2). Because of land-use exclusions in California, which depend on local zoning decisions, it may alternatively be useful to obtain a portion of onshore wind from Wyoming, where wind resources are enormous and underutilized, or from Oregon or Washington.

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Table 2

Number, capacity, footprint area, and spacing area of WWS power generators needed to provide California's total annually averaged all-purpose end-use power demand in 2050, accounting for transmission, distribution, and array losses. Ref. [40] contains spreadsheets used to derive the table.

Energy technology	Rated power of one unit (MW)	Percent of 2050 power demand[a] met by technology	Technical potential nameplate capacity (GW)[b]	Assumed installed nameplate capacity of existing + new units (GW)	Percent of assumed nameplate capacity already installed 2013	Number of new units needed for California	Footprint for new units (percent of California land area)[c]	Spacing for new plants/devices (percent of California land area)
Onshore wind turbine	5	25	238	131,887		4.42	25,211	0.000078	2.77
Offshore wind turbine	5	10	166	39.042		0	7809	0.000024	0.859
Wave device	0.75	0.5	7.5	3.723		0	4963	0.00065	0.031
Geothermal plant	100	5	187.1	9.188		21.8	72	0.0061	0
Hydroelectric plant	1300	3.5	20.9	11.050		100	0[d]	0	0
Tidal turbine	1	0.5	7.4	3.371		0	3371	0.00024	0.0031
Res. roof PV system	0.005	8	83.1	76.237[e]		1.66	14,990,000[e]	0.139	0
Com/gov roof PV system	0.10	6	55.3	54.006[e]		1.17	533,700[e]	0.099	0
Utility PV plant	50	26.5	4122	173.261		0.37	3450[f]	0.320[f]	0
Utility CSP plant	100	15	2726	122.642		0.0	1226[f]	0.579	0
Total		100			624,407	3.4		1.14	3.67
Total new land required								0.90[g]	2.77[h]

Rated powers assume existing technologies. The percent of total demand met by each device assumes that wind and solar are the only two resources that can power California independently (Section 5) and that they should be in approximate balance to enable load matching (Sections 6 and S3). Because of California's extensive solar resources, solar's total share is higher than that of wind's. The number of devices is calculated as the California end-use power demand in 2050 from Table 1 (0.157 TW) multiplied by the fraction of power from the source and divided by the annual power output from each device, which equals the rated power multiplied by the annual capacity factor of the device and accounting for transmission and distribution losses. The capacity factor is determined for each device as in Ref. [40]. Onshore wind turbines are assumed to be located in mean annual wind speeds of 7.5 m/s and offshore turbines, 8.5 m/s [17]. These mean wind speeds give capacity factors (before line losses) of 0.338 and 0.425, respectively, for the 5-MW turbines with 126-m diameter rotors assumed. Footprint and spacing areas are similarly calculated as in Ref. [40]. Footprint is the area on the top surface of soil covered by an energy technology, thus does not include underground structures. Transmission and distribution losses for onshore wind are assumed to range from 5 to 15%; those for offshore and all other energy sources; 5% due to the proximity of offshore to load centers.

[a] Total California projected end-use power demand in 2050 is given in Table 1.

[b] Onshore wind, offshore wind, tidal, and wave estimates are derived in Section 5. Rooftop residential and commercial/government PV estimates are derived in Section S2. The rest is from Ref. [46]. The "technical" potential accounts for the availability of each resource (e.g., wind speed, solar insolation), the performance of the technology, topographic limitations, and environmental and land-use constraints on siting. The technical potential does *not* consider market or economic factors. It also treats each technology in isolation, and not as part of a system, with the result that, for example, some of the technical potential for CSP and some the technical potential for utility PV might be based on the *same* land. The potential for hydro in Ref. [46] was for hydro beyond existing hydro, so that was added to existing hydro here.

[c] The total California land area is 404,000 km^2.

[d] California already produces about 90.6% (4.98 GW of delivered power in 2010) of the hydroelectric power needed under the plan (5.495 GW of delivered power in 2050). The remaining hydro can be obtained as described in the text.

[e] The average capacity factors for residential and commercial/government solar are estimated in Section S4. The nameplate capacity of installed rooftop solar PV is estimated in Section S2.

[f] For utility solar PV plants, nominal "spacing" between panels is included in the plant footprint area. The capacity factor assumed for utility PV is estimated in Section S4. The capacity factor for CSP is 21.5%. These capacity factors assume that most utility PV and CSP are in desert areas.

[g] The total footprint area requiring new land is equal to the footprint area for new onshore wind and geothermal plus that for utility solar PV and CSP plants. Offshore wind, wave and tidal are in water, and so do not require new land. Since no new hydroelectric plants are proposed here (hydro's capacity factor is assumed to increase), hydro does 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).

[h] 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 most of the spacing area for onshore wind can be used for multiple purposes, such as open space, agriculture, grazing, etc.
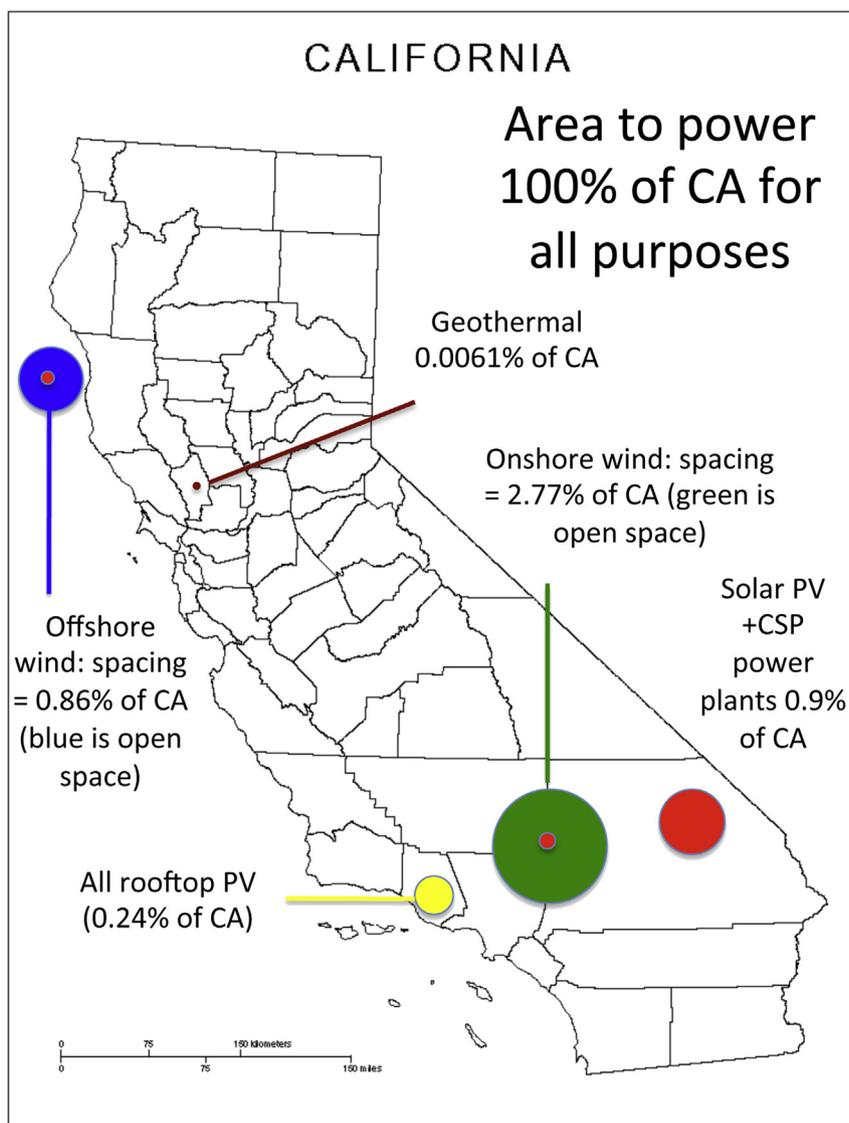
Fig. 1. Spacing and footprint areas required, from Table 2, to repower California for all purposes in 2050. The dots do not indicate the actual location of energy farms. For wind, the small red dot in the middle is footprint on the ground (not to scale) and the green or blue is space between turbines. For others, footprint and spacing are the same. For rooftop PV, the dot represents the rooftop area needed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Dvorak et al. [17] mapped the West Coast offshore wind resources at high resolution (Supplemental information, Fig. S1). Their results indicate that 1.4—2.3 GW, 4.4—8.3 GW, and 52.8—64.9 GW of deliverable power (accounting for exclusions) could be obtained from offshore wind in California in water depths of <20 m, 20—50 m, and 50—200 m depths, respectively. Averaged over the year, the total delivered potential out to 200-m depth is thus 58.6—75.5 GW (or 513—661 TWh/yr), or ~166 GW of installed capacity, which far exceeds the offshore delivered power needed in Table 2 of ~15.7 GW (138 TWh/yr), or the installed capacity needed of ~39 GW.

California solar resources are significant. Both Fig. 3, derived here, and NREL [57] estimate California year-round average surface-incident solar energy of 5—6.15 kWh/m^2/day, or 208—256 W/m^2. Section S2 suggests that this could result in a maximum installed PV capacity in 2050 of about 83.1 GW on residential rooftops and 55.3 GW on commercial/government rooftops, in both cases including carports, garages, parking structures, and parking lot canopies (Table 2).

California currently uses geothermal resources for public power generation, and the state has potential to add capacity. California generated ~2620 MWe through geothermal, or ~5% of the state's annual electricity demand, in 2011 [8]. An additional 1100 MWe is planned to come online [64]. Many geologic fault-lines near underground water sources create potential for more geothermal capacity. The U.S. Geological Survey [75] identified ~5400 MWe of near-term geothermal potential in California with a long-term potential of 11,000 MWe of conventional geothermal and as much as 48,000 MWe through the use of enhanced geothermal systems (EGS). EGS involves low-permeability resources at greater depths than conventional geothermal wells. As of now, though, there is no commercial EGS operating, so we rely on only conventional potential here.

In 2010, conventional hydropower supplied 3.82 GW (33,430 GWh/yr) of electric power to California, representing 16.4% of the state's electric power demand that year [22]. The installed conventional hydroelectric capacity was 10.141 GW [22], of which ~1.58 GW was small (<30 MW) hydro, including run-of-the-river
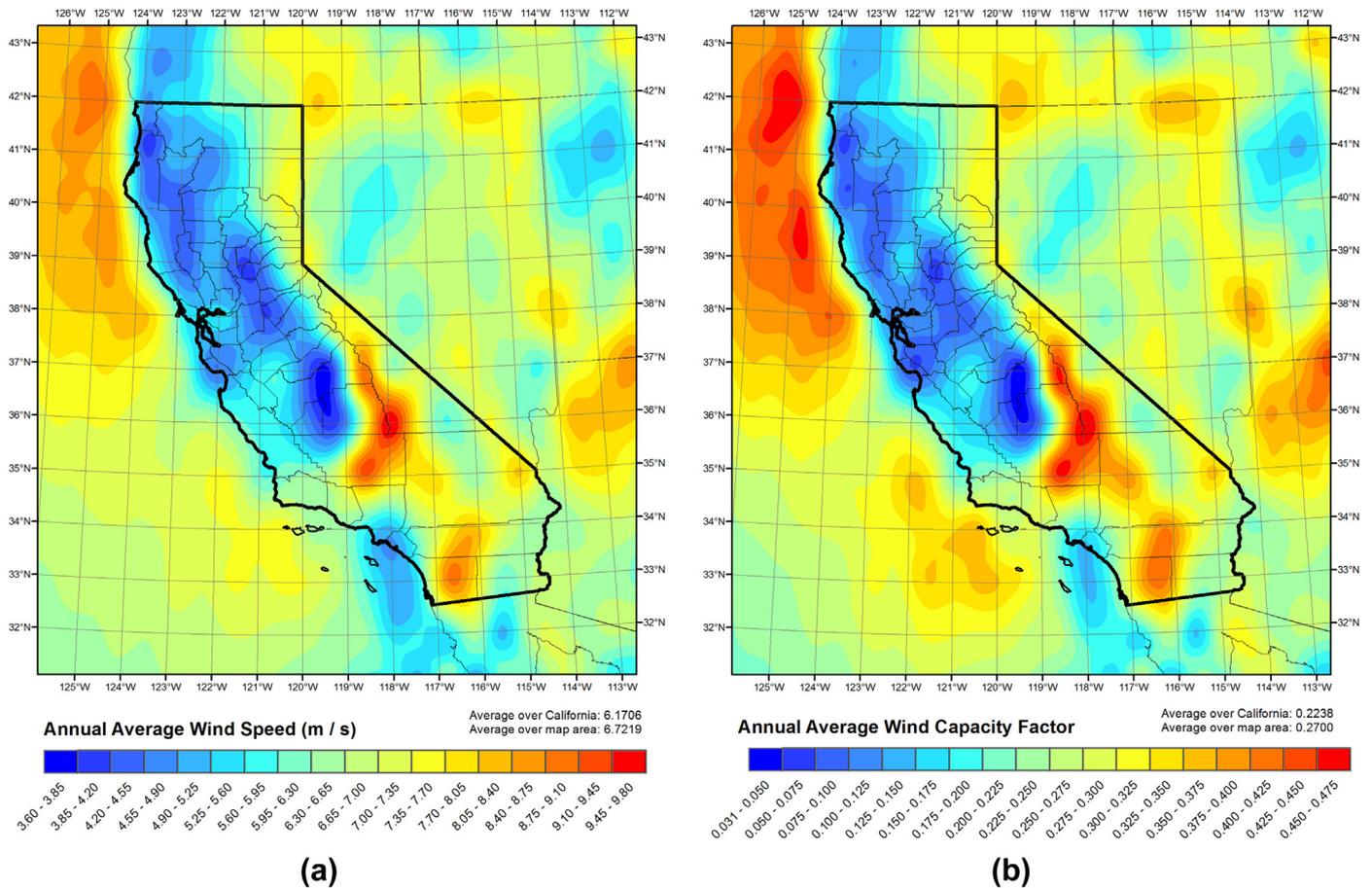
Fig. 2. Modeled, as part of this study, 2006 annual (a, left) wind speeds (m/s) and (b, right) capacity factors for 5 MW RePower wind turbines (126-m diameter rotor) at 100-m hub height above the topographical surface in California and neighboring states. The model used was GATOR-GCMOM [34], which simulates weather, clouds, aerosols, gases, radiation, and surface processes over time. The model was nested from the global to regional scale with resolution on the regional scale of 0.6° W–E × 0.5° S–N.

hydro. Thus, the capacity factor of conventional hydro was 37.7% in 2010.

In addition, California received an estimated 0.455 GW of delivered hydroelectric power from British Columbia. Using a capacity factor of 50%, we assign Canadian hydrocoming to California an approximate installed capacity of 0.909 GW. We include this as part of existing hydro capacity in California in Table 2 (for a total existing California hydro capacity of 11.050 GW) to account for the fact that this may continue to 2050, obviating the need to replace this supply in California. We do not account for imports from U.S. states (e.g., Washington State hydro) since under WWS plans being developed for other states, such hydro may be redirected to internal use or states aside from California. Since Canadian hydro potential is so enormous, we do not believe it will be redirected even if Canada goes to 100% WWS.

In addition, California had 3.813 GW of installed pumped storage in the form of reservoir pairs [22], 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. Pumped storage uses slightly more electricity than it generates, so it is not a "source" of electric power; instead it allows peak power demand to be met reliably and cost-effectively, which will be important in a 100% WWS world.

Under the plan proposed here, conventional hydro will supply 5.5 GW of delivered power, or 3.5% (Table 2) of California's 2050 total end-use power demand for all purposes. Thus, 2010 California plus Canadian hydropower (4.3 GW) already provides 78% of California's 2050 delivered hydropower power goal. The plan here

calls for no new hydroelectric power installation (Table 2). Thus, the additional 1.2 GW of delivered hydro (5.5–4.3 GW) would be obtained by increasing the capacity factor of existing dams in California, which currently provide less than their maximum capacity due to an oversupply of energy available from other sources and multiple priorities affecting water use. Alternatively, [16] estimates that non-powered dams in California can increase their name-plate capacity by 156 MW. Third, DOE [14] estimates that California has 3425 MW of additional potential hydropower generation through low power and small hydro. Finally, more hydropower can be imported from Washington State or British Columbia.

Tidal (or ocean current) plus wave power is proposed to comprise about 0.5% each of California's overall power in 2050 (Table 2). California's 1200 km of coastline has deep-water power fluxes >37 GW, of which up to 20% (7.4 GW) could be converted to tidal power [10]. The present plan calls for extracting only 0.79 GW of delivered power from tides in 2050 (Table 2), about 1/10th the extractable power. However, most current technology tidal devices are designed for high power density locations, such as channels and tidal basins.

Practical ocean wave resources off the California coast (within 10 miles of the coast, in water depth greater than 50 m, and assuming only 20% of the raw resource can be exploited) are estimated as 7.5 GW of installed capacity and 33 TWh/yr of deliverable power [41]. This exceeds the 4.18 GW of installed capacity and 6.0 TWh/yr (0.79 GW) of delivered power proposed for tidal in 2050 in Table 2.
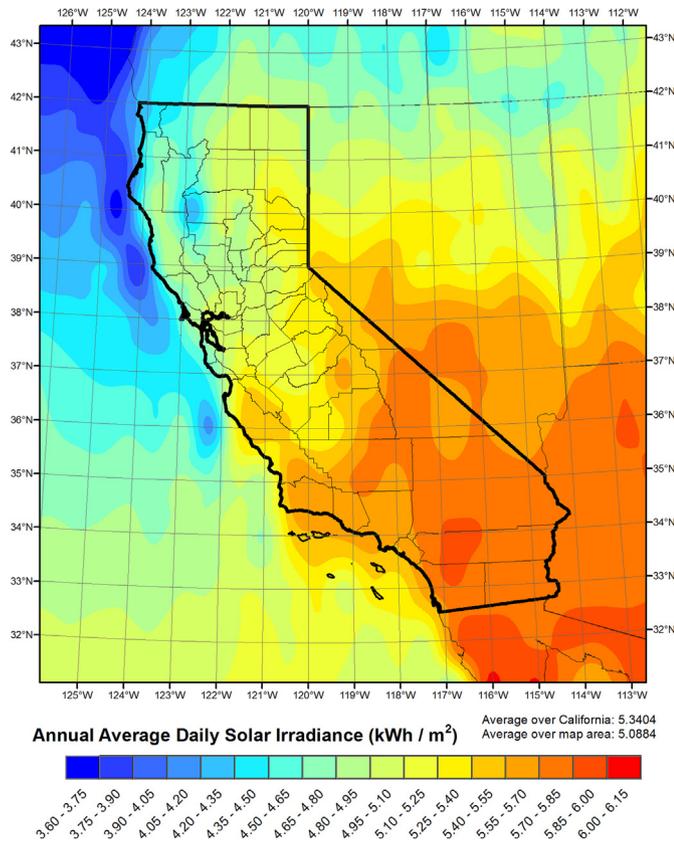
Fig. 3. Modeled, for this study, 2006 annual downward direct plus diffuse solar radiation at the surface (kWh/m²/day) available to photovoltaics in California and neighboring states. The model used was GATOR-GCMOM [34], which simulates weather, clouds, aerosols, gases, radiation, and variations in surface albedo over time. The model was nested from the global to regional scale with resolution on the regional scale of $0.6°$ W–E × $0.5°$ S–N. The resource for California at this resolution ranges from ~5 to 6.15 kWh/m²/day.

6. Matching electric power supply with demand

A question integral to this study is whether conversion to 100% WWS for electricity combined with enhanced electric loads due to electrification of transportation, heating and cooling, and industry can result in a stable electric power supply. Several studies have examined whether renewable energy resources can provide significant portions (up to 100%) of electric power on the grid reliably (e.g., Refs. [6,11,27,30,31,37,47,48,50–52,54,58,62]).

Here, we do not model the reliability of an optimized future California grid but discuss a recent optimization study in which 100% WWS in the California grid was modeled for two years. Hart and Jacobson [30] used a stochastic optimization model of system operation combined with a deterministic renewable portfolio planning module to simulate the impact of a 100% WWS penetration for California every hour of 2005 and 2006. They assumed near-current hydroelectric and geothermal but increased geographically-dispersed time-dependent wind, solar PV, and CSP with 3-h storage. They constrained the system to a loss of load of no more than 1 day in 10 years and used both meteorological and load forecasts to reduce reserve requirements. They found that, under these conditions, 99.8% of delivered electricity could be produced carbon-free with WWS during 2005–2006 (e.g., Fig. S2 for two days).

The result of Hart and Jacobson [30] suggests that, for California, a large part of the intermittency problem of wind and solar can be addressed not only by combining the two, but also by using hydroelectric and CSP with 3-h storage to fill in gaps. The remaining differences between supply and demand can likely be addressed with the inclusion of demand-response management; energy efficiency measures CSP with storage longer than 3 h, additional pumped hydroelectric storage, distributed or large-scale battery storage, compressed-air storage, flywheels, seasonal heat storage in soil, out-of-state WWS resources, the addition of flexible loads such as electric vehicles (e.g. Ref. [49]), vehicle-to-grid methods, and oversizing the number of WWS generators to simplify matching power demand with supply while using excess electricity for district heat or hydrogen production (e.g., Section S3 of the Supplemental Information and Ref. [12]).

The results of Hart and Jacobson [31] are supported further by those of Budischak et al. [6]; who modeled the PJM interconnection in the eastern U.S. over four years and found that up to 99.9% of delivered electricity could be produced carbon-free with WWS resources. As noted, the remaining papers cited above also demonstrate the ability of large penetrations of renewables to match power demand with supply. In sum, a complete and optimized WWS system in California should require no fossil backup but will benefit from hydroelectric and CSP storage.

7. Costs of the WWS versus current infrastructure

This section discusses the current and future full social cost (including capital, land, operating, maintenance, storage, fuel, transmission, and externality costs) of WWS electric power generators versus fossil fuel generators. Because the estimates here are based on current cost data and trend projections for individual

Table 3
Approximate fully annualized generation and short-distance transmission unsubsidized business and externality costs of WWS power and new conventional power (2013 U.S. ¢/kWh-delivered).

Energy technology	2013[a]	2030[a]
Wind onshore	4–10.5[c]	≤4[b]
Wind offshore	11.3[d]–16.4[c]	7[c]–10.9[d]
Wave	11.0–22.0[b]	4–11[b]
Geothermal	9.9–15.2[c]	5.5–8.8[c]
Hydroelectric	4.0–6.0[e]	4[b]
CSP	13.5–17.4[c]	7–8[b]
Solar PV (utility)	10.1–11.4[c]	4.5–7.0[h]
Solar PV (commercial rooftop)	14.9–20.4[c]	6.0–9.8[h]
Solar PV (residential rooftop)	17.8–24.3[f]	6.2–10.0[h]
Tidal	11.0–22.0[b]	5–7[b]
Weighted-average WWS[j]	12.1 (9.9–14.3)	6.2 (5.3–7.2)
New conventional (plus externalities)	9.7 (9.3–10.1)[g] (+5.3[g]) = 15.0 (14.6–15.4)[j]	15.7 (15.0–16.3)[i] (+5.7[g]) = 21.4 (20.7–22.0)

[a] 1 ¢/kWh for transmission was added to all technologies as in Ref. [12] except for distributed generation projects (i.e., commercial and residential solar PV). The externality cost of WWS technologies is < 0.02 ¢/kWh (Table S2).
[b] Ref. [12].
[c] Ref. [43]. Assumes system life of 20 years for solar PV, geothermal, onshore and offshore wind, gas, 40 years for CSP, nuclear, and coal. Assumes 8% interest for 60% of cost 40% equity at 12% cost.
[d] Ref. [44].
[e] Ref. [63].
[f] The residential PV LCOE is calculated by multiplying the [43] commercial LCOE by the ratio of the residential-to-commercial PV $/Watt ($4.72/$3.96) from Ref. [66].
[g] Tables S1 and S2 of the Supplemental Information.
[h] Calculated using the method and assumptions for "Solar PV" in Table A1d of Ref. [12]; with adjustments as explained in Section S4.
[i] Assumes a 2.85% increase in electricity cost per year from 2011 to 2030 for conventional generators, which is the average all-sector price increase in electricity in California from 2000 to 2012 [19].
[j] The weighted-average WWS cost combines the 2050 distribution of WWS generators from Table 2 with the 2013 or 2030 cost of energy from the present table.

generator types and do not account for interactions among energy generators, major end uses, or transmission and storage systems (e.g., wind and solar power in combination with heat pumps and electric vehicles; e.g., Ref. [53]), these estimates are only a rough approximation of what costs will be in a future optimized renewable energy system.

Table 3 presents 2013 and 2030 estimates of fully annualized costs of electric power generation for WWS technologies assuming standard (but not extra-long-distance) transmission and excluding distribution. The future estimates are "approximate" not only because of normal uncertainty in estimating technology costs, but also because of uncertainty in the design and optimization of a future California electric power system, as mentioned above. Table 3 also shows California's 2013 delivered business (private) plus externality (social) electricity costs of conventional fuels (coal, natural gas, and nuclear). The Supplemental information describes the derivation of the overall WWS and conventional fuel private costs in 2013 and 2030, and Table S2 breaks down the externality costs of fossil-fuel electric generation presented in Table 3. Externality costs include the costs of air-pollution morbidity and mortality and global-warming damage (e.g., coastline loss, agricultural and fishery losses, human heat stress mortality and increases in severe weather).

Table 3 indicates that the 2013 costs of onshore wind and hydroelectricity are similar to or less than costs from typical new conventional generators, when externality (social) costs of the conventional technologies are ignored. When externality costs are included, these WWS technologies cost less than conventional technologies today. Solar power presently is more expensive than is conventional power, but its costs have been declining.

With a 100% WWS market penetration proposed for 2050, significant cost reductions are expected due not only to anticipated technology improvements and the zero fuel cost of WWS resources, but also to less expensive manufacturing and streamlined project deployment from increased economies of scale. On the other hand, private electricity costs of conventional fuels are expected to continue to rise in California. The 2030 estimated fossil-fuel private cost is estimated as the 2013 cost grown at a rate of 2.85% per annum, the rate of increase of California's 2000–2012 all-sector electricity prices [19].

Costs of onshore wind and hydroelectric power are expected to remain low in 2030. The cost of wind-generated electricity has declined recently due to the rapid decline in turbine prices and improvements in technology leading to increased net capacity factors (e.g., increases in average hub height and rotor diameter). For example, wind turbines ordered in 2011 declined nearly 20% in price compared with 2008 [78]. Similarly, solar PV costs are expected to fall to 4.5–10 U.S. ¢/kWh by 2030, with the low end for utility-scale solar and the high end, for residential.

Due to the nascent state of the wave and tidal industries (the first commercial power projects have just now been deployed in the United States), it is difficult to make accurate cost estimates (Table 3). Roughly 50 different tidal devices are in the proof-of-concept or prototype development stage, but large-scale deployment costs have yet to be demonstrated [32]. Although current wave power-generating technologies appear to be expensive, they might follow a learning curve similar to that of the wind power industry. Industry analyses point toward a target annualized cost of 5 U.S. ¢/kWh (e.g., Ref. [3]). We estimate 2030 costs at 4–11 U.S. ¢/kWh for wave and 5–7 ¢/kWh for tidal power.

The estimates in Table 3 include the cost of typical transmission distances today. The cost of extra-long-distance transmission is discussed in the Supplemental information. Even with extra-long-distance HVDC transmission, the costs of all WWS resources in 2030 are expected to be much less than the average direct plus externality cost of conventional electricity. Importantly, WWS will provide a stable, renewable source of electric power not subject to the same fuel supply insecurity and price volatility as are fossil fuels and even nuclear power.

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

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

8.1. Air-pollution cost reductions due to WWS

To estimate air-pollution damage costs, we first estimate total premature mortality due to air pollution with a top-down approach that relies on computer simulations and a bottom-up approach that relies on analyzing air quality data in California.

The top-down approach to estimate air-pollution mortality in California. 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. First, 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. Braga et al. [5] estimate the U.S. air-pollution premature mortality rate at about 3% of all deaths, giving ~78,000/year. Similarly, Jacobson [36] calculated the U.S. premature mortality rate due to ozone and particulate matter with a three-dimensional air pollution-weather model to be 50,000–100,000 per year. Third, McCubbin and Delucchi [55] estimated 80,000–137,000 premature mortalities/yr due to all anthropogenic air pollution in the U.S. in 1990, when air-pollution levels were higher than today. Multiplying an estimated 50,000–100,000 premature mortalities/yr by 12.2%, the fraction of the U.S. population in California, gives 6100–12,200 annual premature mortalities in California from the top-down approach. Since a large segment of California' population lives in cities, and California has a majority of the top polluted cities in the U.S., this estimate is likely low.

The bottom-up approach to estimate air-pollution mortality in California. 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 U.S. Census Bureau population by county. From these three pieces of information, low, medium, and high estimates of mortality due to $PM_{2.5}$ and O_3 pollution are calculated with a health-effects equation (e.g., Ref. [36]).

Table S3 of the Supplemental information shows the resulting low, medium, and high estimates of premature mortality in California due to $PM_{2.5}$ and ozone, for 2010–2012 The medium values for the state as a whole were ~10,000 (2600–19,400) premature mortalities/yr for $PM_{2.5}$ and ~2500 (1300–3800)/yr for ozone, for an overall bottom-up estimate of ~12,500 (3800–23,200) premature mortalities/yr for $PM_{2.5}$ plus O_3. The top-down estimate (6100–12,200) is slightly lower because the top-down approach did not account for the greater severity of air pollution in California cities than in average U.S. cities.

Mortality and Nonmortality costs of air pollution. In general, the value of life is determined by economists based on what people are willing to pay to avoid health risks [65]. USEPA [73] and Levy et al. [45] provided a central estimate for the statistical value of a human life at $7.7 million in 2007 dollars (based on 2000 GDP). Other costs due to air pollution include increased illness (morbidity from

chronic bronchitis, heart disease, and asthma), hospitalizations, emergency-room visits, lost school days, lost work days, visibility degradation, agricultural and forest damage, materials damage, and ecological damage. USEPA [74] estimates that these nonmortality-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, other studies in the economics literature indicate considerably higher nonmortality costs. McCubbin and Delucchi's [55] comprehensive analysis of air-pollution damages at every air quality monitor in the U.S. found that the morbidity cost of air pollution (mainly chronic illness from exposure to particulate matter) might be as high as 25–30% of the mortality costs. Delucchi and McCubbin [13] summarize studies that indicate that the cost of visibility and agriculture damages from motor-vehicle air pollution in the U.S. is at least 15% of the cost of health damages (including morbidity damages) from motor-vehicle air pollution. Thus, the total cost of air pollution, including morbidity and non-health damages, is at least ~$8.2 million/mortality, and probably over $10 million/mortality.

Given this information, the total social cost due to air-pollution mortality, morbidity, lost productivity, and visibility degradation in California is conservatively estimated to be $103 (31–232) billion/yr (using $8.2 million/mortality for the low and medium numbers of mortalities and $10 million/mortality for the high number), based on the California mortalities estimated here due to 2010–2012 air pollution. Eliminating these costs represents a savings equivalent to ~4.9 (1.5–11.2) % of California's gross 2012 domestic product of $2.08 trillion. We expect that the benefits of eliminating fossil-fuel use in the future will be similar, because on the one hand increasingly stringent future pollution regulations are likely to reduce emissions per unit energy use, but on the other hand, future growth in population and economic activity will increase both total energy use (which will tend to increase total emissions), the spread of pollution to larger areas, and total exposure to pollution.

8.2. Global-warming damage costs eliminated by 100% WWS in California

Energy-related emissions from California inflict global-warming damage to the state, the U.S., and the world. In this section, we provide a rough estimate of these damages, which a 100% WWS system in California would eliminate, by extrapolating climate cost estimates from other studies.

Table 4 estimates the global-warming cost from California's own energy-related and overall greenhouse-gas emissions in 2020. Results were obtained by multiplying CO_2 or CO_2-equivalent emissions in California by the social cost of carbon (SCC). The 2020 "best guess" costs from California's energy-related emissions and overall emissions are ~$45 billion/yr and ~$54 billion/yr, respectively. If emissions increase further past 2020, then the global-warming damage from California's energy use will well exceed $50 billion/year.

The following alternative calculation yields a similar result. Ackerman et al. [1] estimated global-warming damage costs (in 2006 U.S. dollars) to the U.S. alone of $271 billion/yr in 2025, $506 billion/yr in 2050, $961 billion/yr in 2075, and $1.9 trillion/yr in 2100. That analysis accounted for severe-storm and hurricane damage, real estate loss, energy-sector costs, and water costs. The largest of these costs was water costs. The estimate did not account for increases in mortality and illness due to increased heat stress, influenza, malaria, and air pollution or increases in forest-fire incidence, and as a result, probably underestimates the true cost. In 2010, California contributed to 6.61% of U.S. and 1.121% of world fossil-fuel CO_2 emissions [18]. Since the global-warming damage cost to the U.S. is caused by emissions from all states and countries worldwide, California's energy-related contribution to U.S. damages is found by multiplying the cost of global warming to the U.S. by California's fraction of global CO_2 emissions and the fraction of total CO_2 emissions that are energy-related (~0.85). The resulting costs to the U.S. of California's energy-related emissions are $2.6 billion/yr in 2025; $4.8 billion/yr in 2050; $9.2 billion/yr in 2075; and $18.1 billion/yr in 2100.

Anthoff et al. [2] then found that damages to the world are at least an order of magnitude higher than are damages to the U.S. alone. Thus, worldwide global-warming cost damages from all California energy-related emissions might be ~$48 billion/yr in 2050. The worldwide damage estimate from energy-related California emissions from Table 4 was similar, ~$45 billion/yr.

In sum, converting to WWS would avoid $103 billion/year in air-pollution health costs to California, ~$4.8 billion/yr in global-warming damage costs to the U.S., and ~$48 billion/yr in global-warming damage costs to the world by 2050. The mean installed capital cost of the electric power system proposed here, weighted by the installed capacity of each generator, is approximately $1830/kW. Thus, for a nameplate capacity summed over all new generators needed for the plan (603 GW, versus 624 GW of new plus existing generators needed from Table 2 to provide 157 GW of end-use all-purpose power in 2050 from Table 1), the total additional installed capital cost of a WWS system is ~ $1.1 trillion. As such, the health-cost savings alone due to converting to WWS may equal the installation cost of WWS generators within 11 (5–35) years. The savings in health cost to California plus climate cost to the world may equal the generators within 7 (4–14) years.

9. Impacts of WWS on jobs and labor earnings due to new electric power plants

This section estimates jobs and total earnings created by implementing WWS-based electricity and 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.

Table 4
Global-warming cost ($billions/yr) due to California's own emissions estimated by multiplying BAU carbon-equivalent emissions by the social cost of carbon (SCC).

California emission sector	2020	
	Low-estimate	Best guess
Electricity generation	2.37	12.5
Transportation	3.83	20.3
Commercial and residential	0.79	4.20
Industrial	1.71	9.05
Recycling and waste	0.13	0.69
Agriculture and forestry	0.51	2.68
High GWP gas release	0.80	4.22
Total cost all emission sectors	10.1	53.7
Total cost, energy-related sectors	8.51	45.1

Global-warming costs equal CO_2-equivalent emissions in each sector in 2020 [7] multiplied by a low or "best guess" estimate of the SCC. Krewitt and Schlomann [42] recommend USD_{2005} $17/t CO_2 as a lower-limit SCC benchmark value for global decision-making. The IPCC SRREN [29] report gives $90/t CO_2 as a "best guess" estimate of the SCC. Energy-related sectors exclude recycling and waste, high GWP gas release, most of agriculture and forestry, and clinker production from the cement industry (under "Industrial"). BAU, business as usual.

9.1. A. JEDI job creation analysis

Changes in jobs and total earnings are estimated here first with the Jobs and Economic Development Impact (JEDI) models [15]. These are economic input–output models programmed by default for local and state levels. They incorporate three levels of impacts: (1) project development and onsite labor impacts; (2) local revenue and supply-chain impacts; and (3) induced impacts. Jobs and revenue are reported for two phases of development: (1) the construction period and (2) operating years.

Scenarios for wind and solar powered electricity generation were run assuming that the WWS electricity sector is fully developed by 2050. Existing capacities were excluded from the calculations. As construction period jobs are temporary in nature, JEDI models report job creation in this stage as full-time equivalents (FTE, equal to 2080 h of work per year). We assume for this simplistic calculation that each year from 2010 to 2050 1/40th of the WWS infrastructure is built. All earnings are reported in 2010 real U.S. dollar values.

Specific JEDI models were not available for geothermal electricity generation. Therefore, job creation for those projects were extrapolated from another study. Table 5 summarizes job and revenue creation from the installation and use of each WWS resource. Section S6 contains more detail about the scenarios. In sum, the JEDI models predict the creation of ~442,200, 40-year construction jobs and 190,600 permanent jobs for operation and maintenance of the projects proposed before job losses are accounted for. The majority of these jobs are in the solar industry.

9.2. Job loss analysis

Table 6 provides estimates of the number of California jobs that will 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 were calculated.

Although the petroleum industry will lose jobs upon eliminating the extraction of crude oil in California, ~5000 jobs in the production of non-fuel petroleum commodities such as lubricants, asphalt, petrochemical feedstocks, and petroleum coke will remain. This is estimated as follows: currently, 195,000 people work in oil and gas production alone across the U.S. [68]. Assuming 50% of these workers are in oil production, 97,500 jobs exist in the U.S. oil

Table 6
Job loss upon eliminating energy generation from fossil-fuel and nuclear sectors.

Energy sector	Number of jobs lost
Oil and gas extraction/production	73,900[a]
Petroleum refining	7900[b]
Coal/gas power plant operation	14,500[c]
Uranium mining	460[d]
Nuclear power plant operation	3400[e]
Coal and oil transportation	297,000[f]
Other	20,800[g]
Less petroleum jobs retained	−5000[h]
Total	413,000

[a] Ref. [28].
[b] Workers employed in U.S. refineries from Ref. [24] multiplied by fraction of U.S. barrels of crude oil distilled in California from Ref. [25].
[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. [67]. All other data from ONET [60] online.
[d] Multiply U.S. uranium mining employment across 12 U.S. states that mine uranium from Ref. [26] by the fraction of California population in those 12 states.
[e] Ref. [56].
[f] Multiply the total number of direct U.S. jobs in transportation (11,000,000) from USDOT [72] by the ratio (0.287 in 2007) of weight of oil and coal shipped in the U.S. relative to the total weight of commodities shipped from USDOT [71] and by the fraction of transportation jobs that are relevant to oil and coal transportation (0.78) from the U.S. Bureau of Labor Statistics [69] and by the fraction of the U.S. population in California.
[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, Ref. [61].
[h] See text for discussion of jobs retained.

production industry. California currently produces 9.5% of crude oil in the U.S. [20], suggesting ~9750 workers in California oil production. California's oil refineries employ another 8000 workers (Table 6). Nationally, the non-fuel output from oil refineries is ~10% of refinery output [23]. We thus assume that only 10% (~1800) of petroleum production and refining jobs will remain upon conversion to WWS. We assume another 3200 will remain for transporting this petroleum for a total of 5000 jobs remaining.

In sum, the shift to WWS may result in the displacement of ~413,000 jobs in current fossil- and nuclear-related industries in California. At $60,000/yr per job — close to the average for the WWS jobs in Table 5 — the corresponding loss in revenues is ~$24.8 billion.

Table 5
Summary of job and earnings creation and loss during the construction and operations of WWS energy generators, assuming the 2050 new installed capacities derived from Table 2.

	New capacity (MW)	Construction period		Operation period	
		40-yr-Jobs[a]	Earnings (billion $/yr)	40-yr Jobs[b]	Earnings (billion $/yr)
Onshore wind	123,600	12,500	0.790	19,100	1.61
Offshore wind	39,000	7120	0.518	25,700	1.69
Wave	3720	1300	0.086	9000	0.60
Geothermal	7180	3500	0.191	530	0.056
Hydroelectric	0	0	0	0	0
Tidal	3370	1030	0.068	7800	0.522
Res. roof PV	75,400	120,700	6.22	35,700	2.06
Com/gov/roof PV	53,600	94,600	5.07	17,500	1.03
Utility PV	169,600	169,400	8.71	52,300	3.01
Utility CSP	123,000	32,100	2.95	23,000	$1.45
Total WWS	598,200	442,200	24.6	190,600	12.0
Job or earnings loss				413,000	24.8
Net gains WWS				+219,800	+11.8

[a] 40-Year jobs are 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.

9.3. Jobs analysis summary

The roadmap proposed here will create a net of 220,000 40-year construction plus operation jobs (442,200 new 40-yr construction jobs and 190,600 new 40-yr operation jobs, less 413,000 jobs lost in current California fossil- and nuclear-based industries). The direct and indirect earnings from WWS amount to $24.6 billion/yr during construction and $12.0 billion/yr during the operating stage (Table 5). The lost earnings lost from fossil-fuel plus nuclear industries will be~$24.8 billion/yr, giving a 40-yr construction plus operation job net earnings upon converting to WWS of ~$11.8 billion/yr.

10. Timeline for implementation of the plan

Fig. 4 shows one timeline scenario for the implementation of this plan in California. Other scenarios are possible. The plan calls for all new electric power generators installed by 2020 to be WWS generators and existing conventional generator to be phased out gradually, such that by 2030, 80–85% of the existing infrastructure is converted and by 2050, 100%. Similarly, all new heating and cooling technologies are proposed to be WWS technologies by 2020 and existing technologies are proposed to be replaced over time, but by no later than 2050.

For transportation, the transition to BEVs and HFCVs is expected to occur more rapidly than in the power generation sector due to the rapid turnover time of the vehicle fleet (~15 years) and the efficiency of BEVs and HFCVs over fossil-fuel combustion vehicles. BEVs and HFCVs exist today, but are anticipated to be the only new vehicles sold in California by 2020. Freight and passenger rail, freight trucks, tractors, construction machines, ships, and aircraft also will be converted to 100% WWS with a combination of electric and hybrid electric-hydrogen fuel cells or, in the case of aircraft, electric-cryogenic hydrogen-energy systems. The vehicle charging and hydrogen fueling infrastructures will need to be developed. With hydrogen fueling, onsite electrolysis using transmitted

electricity to produce hydrogen may be more efficient than producing hydrogen remotely and piping it to fueling stations. For overviews of the development of pathways for electric and hydrogen-fueled transportation, see Refs. [4] and [59].

11. Recommended first steps

Below are recommended short-term policy steps to jump-start the conversion to WWS in California.

Large energy projects: offshore/onshore wind; solar PV/CSP, geothermal, hydro

- Extend the renewable portfolio standard (RPS) in California. The 33% RPS currently sunsets in 2020. Ramp up the RPS 3% per year to achieve 63% by 2030.
- Set a goal of at least 5000 MW of offshore wind by 2030 within the RPS.
- Lock in remaining in-state coal-fired power plants to retire under enforceable commitments. Simultaneously, streamline the permit approval process for WWS power generators and the associated high-capacity transmission lines and eliminate bureaucratic hurdles involved in the application process. Promote expanding transmission of power between upstate and downstate, in particular, to eliminate imported electricity supplied by large coal-fired plants in Arizona, Nevada, Utah, and New Mexico and use existing interstate transmission for renewables.
- Work with regions and localities and the federal government (in the case of offshore wind) and within existing regional planning efforts to manage zoning and permitting issues or pre-approve sites to reduce the costs and uncertainties of projects and expedite their physical build-out.

Small energy projects: residential commercial, and government rooftop solar PV

- Expand budgets for the program authorities of the Go Solar California! campaign, especially administrators of the Multi-Family Affordable Housing program.
- Set up a Green Bank, which is a vehicle for public-private financing, in conjunction with distributed generation (DG) and energy efficiency projects. Example Green Banks exist in Connecticut and New York. Given the relatively comparable financing rates for large-scale WWS projects and conventional energy projects in CA, a Green Bank might best be situated to provide debt financing for on-bill repayment (OBR) and property assessed clean energy (PACE) programs, along with financing for distributed rooftop PV. A Green Bank can streamline inefficient project permitting processes and increase the flow of cheaper capital to currently underserved DG markets.
- Implement virtual net metering (VNM) for small-scale energy systems. VNM is a policy measure that allows a utility customer to assign the net production from an electrical generator on his or her property (e.g., solar PV) to another metered account that is not physically connected to that generator. This allows credits from a single solar PV system to be distributed among multiple electric service accounts, such as in low-income residential housing complexes, apartment complexes, school districts, multi-store shopping centers, or a residential neighborhood with multiple residents and one PV system. The following four recommendations will render utility-scale wind and solar power net metering conducive to corporate clients and pave the way for a more widespread subscription to offsite generating projects for the public:
  1) Remove the necessity for subscribers to have proprietorship in the energy-generating site. This is an unnecessary obstacle
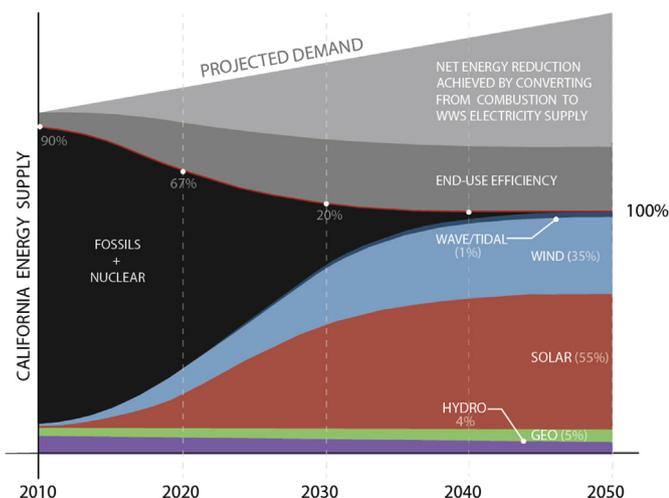

Fig. 4. Change in percent distribution of California energy supply for all purposes (electricity, transportation, heating/cooling, industry) among conventional fuels and WWS energy over time based on the roadmap proposed here. Total power demand decreases over time due to energy reductions due to conversion to WWS and efficiency. The percentages above the fossils plus nuclear curve are of remaining penetration of those energy sources each decade. The percentages next to each WWS source are the final estimated penetration of the source. The 100% demarcation indicates that 100% of all-purpose power is provided by WWS technologies by 2050, and the power demand by that time has decreased. Neither the percentages each year nor the final percentages are exact – they are estimates of one possible scenario.

that enables only multi-property owners to invest in offsite renewables.

2) Expand or eliminate the capacity limit of renewable power under remote net metering for each utility.
3) Remove the barrier to inter-load zone transmission of net-metered renewable power. A utility-scale wind farm downstate has the potential to service subscribers in San Francisco, whose constituents might pay high rates for renewable power and thus stimulate the downstate regional economies.
4) Expand AB 920 to reduce red tape and enable offsite virtual net metering across the state.

- Streamline the small-scale solar and wind installation permitting process. In many places, municipalities have their own permitting process and fee structure. Creating common codes, fee structures, and filing procedures across a state would reduce a barrier to the greater implementation of small-scale solar and wind. Efforts are being made in this direction through the implementation of the Governor's Permitting Handbook and the U.S. Department of Energy's SunShot grant.
- Expand the development of community renewable energy facilities, whereby a community buys power from a centralized generation facility (as currently contemplated under SB43). The facility feeds power into the grid, and the utility credits the kilowatt-hours to the accounts of individuals, businesses, and any other electricity customer that sign up. The facility may be located anywhere in the utility's service territory, since all that is required is a bill-crediting arrangement by the utility. This brings many advantages: economies of scale of the facility, siting in an ideal location, and broader inclusiveness. Many electricity users (~45% of Californians) cannot install a renewable energy system because they are renters or because their property is not suitable for a system. Community renewable energy is inclusive because it enables anyone, whether living in rural California or an apartment building in Los Angeles, to buy the power without having to host the system.
- Pilot a community-based renewable energy self-generation program similar to the one proposed in California's SB 843. Such a pilot would help determine administrative costs of managing such a system and the role of net-zero consumers in paying for grid services as it relates to their effects on non-participating customers. Resulting renewable generation should count toward the requirements mandated by California's RPS. Use as a model the successful uptake of community solar gardens and meter aggregation in Colorado State, as well as the SolarShares program administrated by the Sacramento Municipal Utility District (SMUD).
- Encourage clean energy backup emergency power systems rather than diesel/gasoline generators at both the household and community levels. For example, 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.
- Expand the use of feed-in tariffs (FITs) for small-scale energy systems, as has been done by SMUD and the Los Angeles Department of Water and Power (LADWP). Scale up the LADWP program and substitute it for the state version of the FIT in SB32.
- Promote the increased use of crowd funding to fund small and medium-scale clean energy projects.

Energy efficiency in buildings and the grid
- The current target for energy efficiency is ~1% annual energy savings in electricity through 2020. Expand the target to 2% immediately and above 2% after 2020, and increase investment fivefold from both public and private sources. This requires the

California Public Utilities Commission to increase utility requirements and budgets for efficiency.
- Promote, through municipal financing, incentives, and rebates, energy efficiency measures in buildings, appliances, and processes. Efficiency measures include improving 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, performing an energy audit to discover energy waste, converting to LED light bulbs, changing appliances to those using less electricity, and using hot water circulation pumps on a timer.
- Further incentivize the use of efficient lighting in buildings and on city streets.
- Encourage conversion from natural gas water and air heaters to heat pumps (air and ground source) and rooftop solar thermal hot water pre-heaters.
- Encourage utilities to use demand-response grid management to reduce the need for short-term energy backup on the grid.
- Institute, through the Governor's Office of Business and Economic Development (Go-Biz), a revolving loan fund to pay for feasibility analyses for commercial Energy Services Agreements. The revenues from these retrofits are amortized as a majority percentage of the Energy-Cost Savings realized as a result of retrofits. Allocate some of these revenues back to the fund to render it sustainable.
- Provide incentives to extract heat in the summer and cold in the winter from the air and solar devices and store it in the ground for use in the opposite season.
- Provide incentives to recover heat from air conditioning systems and use it to heat water or air.
- Provide incentives to extract heat (or cold) from the ground, air, or water with heat pumps and use it to heat (or cool) air or water.
- Provide incentives to recover heat from water used to cool solar PV panels to heat water directly for domestic use.

As suggested by Ref. [9]:

- Publicize ground source heat pumps as a key energy efficiency technology for California, by retrofitting a high-profile state building.
- Designate a statewide technology advisory board for ground source heat pump technology.
- Consider closed-loop bores in the regulatory process as something separate from water wells.
- Centralize state-level permit administration.
- Integrate ground-source heat pumps formally within the California FIRST property assessed clean energy program energy efficiency loading order as an approved technology.

Transportation
- Coordinate the recommendations in this subsection so that vehicle programs and public charging stations are developed together. Create a governor-appointed EV Advisory Council, as 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 offleets of electric and/or hydrogen fuel cell/electric hybrid vehicles, ferries, riverboats, and other shipping.
- Encourage and ease the permitting process for the installation of electric charging stations in public parking lots, hotels, suburban metro stations, on streets, and in residential and commercial garages.
- Set up time-of-use electricity rates to encourage charging at night.
- Use excess wind and solar produced by WWS electric power generators to produce hydrogen (by electrolysis) for transportation and industry and to provide district heat for water and air (as done in Denmark) instead of curtailing the wind and solar.
- Encourage the electrification of freight rail and shift freight from trucks to rail.
- Encourage more use of public transit.
- Increase safe biking and walking infrastructure, such as dedicated bike lanes, sidewalks, crosswalks, timed walk signals, etc.
- Offer metropolitan areas increased technical assistance in drafting land-use plans to meet SB 375.

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 onsite electric power (private) generation.

12. Summary

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

The roadmap proposed that all new installations be WWS by 2020 and existing infrastructure be gradually replaced, with about 80–85% replacement by 2030 and 100% replacement by 2050. The conversion from combustion to a completely electrified system for all purposes was calculated to reduce California's 2050 end-use power demand ~44% and hypothesized to stabilize energy prices since fuel costs will be zero. End-use energy efficiency measures more aggressive than were assumed here would reduce power demand further.

The roadmap specifies, based on resource analysis but not optimization modeling, that all-purpose 2050 California end-use power demand could be met with 25% onshore wind (25,200, 5-MW turbines beyond existing turbines), 10% offshore wind (7800, 5-MW turbines), 15% CSP (1230, 100-MW plants), 26.5% solar PV power plants (3450 new 50-MW plants), 8% residential rooftop PV (15.0 million new 5-kW systems), 6% commercial/government rooftop PV (534,000 new 100-kW systems), 5% geothermal (72, 100-MW new plants), 0.5% wave (4960, 0.75-MW devices), 0.5% tidal (3370, 1-MW turbines), and 4% hydro (but no new hydroelectric power plants). This is just one plausible mix. Least-cost energy-system optimization studies and practical implementation considerations will determine the actual design and operation of the energy system and may result in technology mixes different than proposed here (e.g., more power plant PV, less

rooftop PV). The siting of generating facilities would be governed by environmental and zoning regulations.

The additional footprint on land for WWS devices is equivalent to about 0.90% of California's land area, mostly for utility-scale CSP and PV. An additional on-land spacing area (space between devices) of about 2.77% 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 in the proposed scenario can be reduced by shifting more land based WWS generators to the ocean, lakes, and rooftops.

2020–2030 unsubsidized electricity costs are estimated to be 4–11 U.S. ¢/kWh for all WWS technologies (including local transmission and distribution), which compares with about 20.7-22.0 ¢/kWh for fossil-fuel generators in 2030 (Table 3), of which 5.7 ¢/kWh are externality costs (Table and S2). Extra-long-distance transmission costs on land are estimated to be 1 (0.3–3) ¢/kWh for 1200–2000 km high-voltage direct current transmission lines.

The plan is anticipated to create ~442,200, 40-year construction jobs and ~190,600, 40-year operation jobs while costing ~413,000 jobs, resulting in a net job gain of ~220,000 40-year jobs for the construction and operation of new electric power-generating facilities alone. Total earnings during the construction period for these facilities (in the form of wages, local revenue, and local supply-chain impacts) are estimated to be ~$24.6 billion/yr in 2010 dollars and annual earnings during operation of the WWS facilities are estimated to be ~$12.0 billion/yr. Earnings lost by the fossil-fuel and nuclear industries are estimated at ~$24.8 billion/yr, resulting in net positive job earnings over 40 years of ~$11.8 billion/yr.

The plan is estimated to reduce California air-pollution mortality and its costs by ~12,500 (3800–23,200)/yr and $103 (31–232) billion/yr, or 4.9 (1.5–11.2) % of California's 2012 GDP. California's own emission decreases are expected to reduce 2050 U.S. and worldwide global-warming costs by at least $4.8 billion/yr and $48 billion/yr, respectively.

The California air-pollution-reduction benefits of the 100% WWS plan is estimated to pay back the installed $1.1 trillion capital cost of the entire WWS system in 11 (5–35) years. Adding the benefits to global climate from reducing California emissions shortens the pay back time to 7 (4–14) years.

This roadmap can serve as a template for plans in other states and countries. The implementation of similar plans worldwide should essentially eliminate energy-related global warming and energy insecurity, while creating jobs.

Acknowledgments

Supplemental information

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Supplemental Information

A Roadmap for Repowering California for all Purposes with Wind, Water, and Sunlight

Energy

July 15, 2014

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This supplemental information contains additional description, tables, and figures supporting the main text of this study, which analyzes the technical and economic feasibility of repowering California for all purposes with wind, water, and sunlight (WWS).

S1. Introduction

This paper presents a roadmap to convert California's energy infrastructure in all sectors to one powered by wind, water, and sunlight (WWS).

S2. Additional Information on WWS Resources Available

S2.A. West Coast offshore wind

Dvorak et al. (2010) mapped West Coast offshore wind resources at high resolution (Figure S1) and concluded that 1.4-2.3 GW, 4.4-8.3 GW, and 52.8-64.9 GW of deliverable power could be obtained from offshore wind in California in water depths of <20 m, 20-50 m, and 50-200 m depths, respectively. Averaged over the year, the total delivered potential is thus 58.6-75.5 GW (or 513-661 TWh/yr).

Figure S1. Offshore wind speeds and power density at 80 m hub height out to 200-m depth for 2005-2007, modeled at high resolution (5 km x 5 km) as well as the California transmission system (Dvorak et al., 2010).
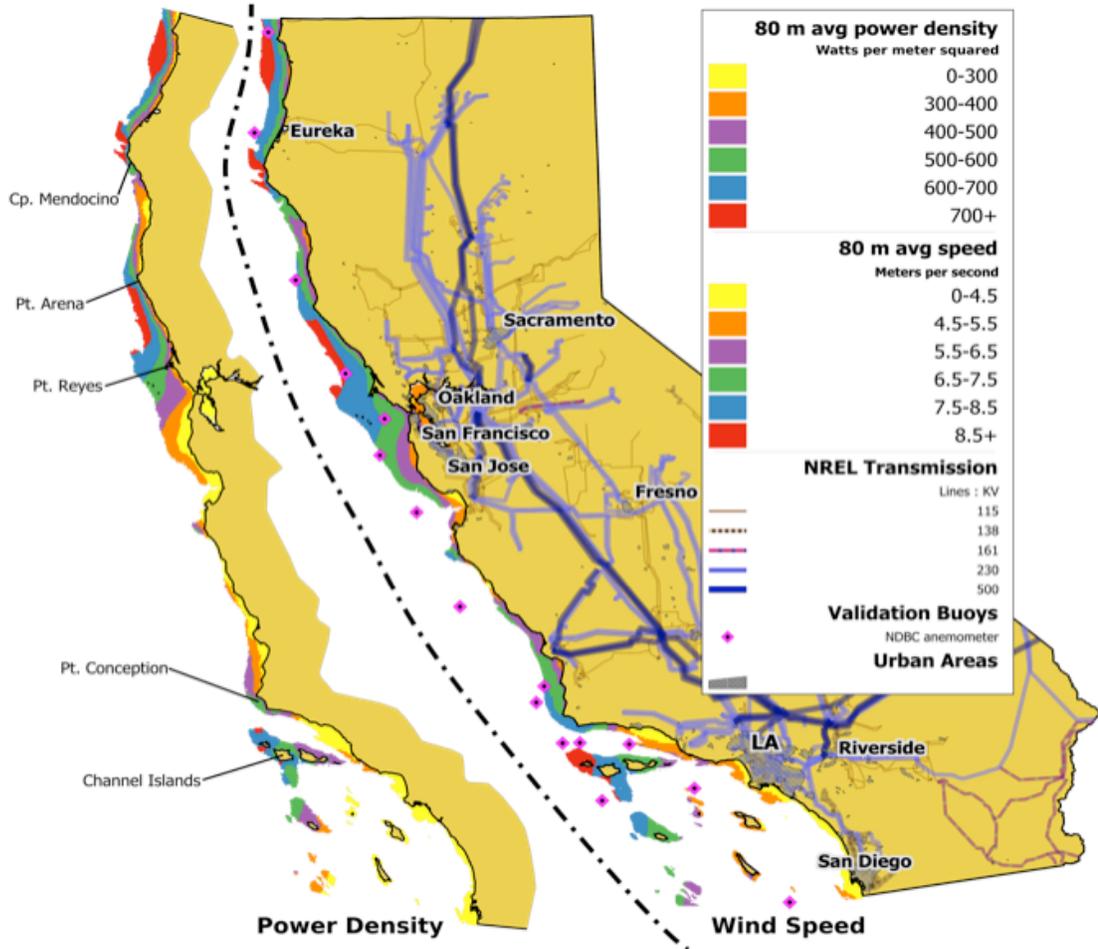
S2.B. Technical potential rooftop photovoltaic (PV) capacity

In the main text, we estimated California's year-round average surface-incident downward solar irradiance to be 208 to 256 W/m^2. Here, we estimate how this average statewide incident solar irradiance translates to potential rooftop PV installed capacity in California in the year 2050, which is the year of the estimates in Table 2 of the main text. Rooftops

include those on residential and commercial/governmental buildings as well as garages, carports, roads, parking lots, and parking structures associated with each. Commercial/governmental buildings include all non-residential buildings except manufacturing, industrial, and military buildings. Commercial buildings include schools.

The potential rooftop PV installed capacity in 2050 equals the potential alternating-current (AC) generation from rooftop PV in 2050 divided by the PV capacity factor in 2050. We perform this calculation for four situations: residential and commercial/government rooftop PV systems in each warm and cool climate zones.

The year 2050 PV capacity factors for the four situations (residential-warm, residential-cool, commercial/government-warm, commercial/government-cool) are estimated in section S4. The potential AC generation from rooftop PV in 2050 is set equal to the solar power incident on potential rooftop PV-panel area in 2050 multiplied by the average PV module conversion efficiency in 2050, which is set equal to the efficiency in 2012 (14.5%; DOE, 2012 and product literature available on the web) multiplied by an assumed 0.85%/year increase in efficiency (based on projections in DOE, 2012).

The solar power incident on potential rooftop PV panel area in 2050 equals the potential in 2012 multiplied by the increase in the potential rooftop area for PV. We assume that the area of residential rooftops (excluding garages and carports) increases at the projected rate of population increase in California (0.7%/year; California Department of Finance, 2014b), and that the area of residential parking rooftops increases at a slightly higher rate, 0.84%/year, to account for people covering previously uncovered parking spaces specifically to install PV. We assume that the area of commercial/government rooftops (excluding parking lots) increases at the product of the rate of increase in

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population (see above) and the rate of increase in the ratio of commercial building area to population (0.08%/year; Kavalec and Gorin, 2009).

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

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

The total commercial/government rooftop area in 2012 is based on the commercial/government floor space per person in 2012 (Kavalec and Gorin, 2009), the state

population in 2012 (California Department of Finance, 2014a), the ratio of roof area to floor space (our estimate based on data in EIA, 2008), and assumptions regarding the fraction of buildings with pitched roofs (our estimates based on data in EIA, 2008). We then assume that the area of parking-lot roofs built for PV is 10% of the commercial rooftop area. See the spreadsheet in Jacobson et al. (2014) for details.

With these assumptions and methods, we estimate that, in 2012, residential and commercial/government rooftops (excluding garages and carports) could support 76 GW of installed PV in California, which is the same as NREL's estimate for California (excluding garages and carports) using a similar method (Lopez et al., 2012). Our estimate of the technical potential rooftop-PV capacity in 2050, including garages and carports, is shown in Table 2 of the main text.

S3. More Information on Matching Electric Power Supply with Demand

In this section, methods for reliably matching variable renewable energy supply with demand over minute-by-minute to seasonal and annual time scales are discussed.

S3.A. Combining WWS Resources as a Bundled Set of Resources

Several studies have examined whether up to 100% penetrations of WWS resources could be used reliably to match power demand (e.g., Jacobson and Delucchi, 2009; Mason et al., 2010; Hart and Jacobson, 2011, 2012; Connolly et al., 2011; Mathiesen et al., 2011; Heide et al., 2011; Elliston et al., 2012; NREL, 2012; Rasmussen et al., 2012; Budischak et al., 2013; Rodriguez et al., 2014). Both Hart and Jacobson (2011) and Budischak et al. (2013) found that up to >99.8% of delivered electricity could be produced carbon-free with WWS

resources over multiple years. The former study obtained this conclusion for the California grid over two years; the latter, over the PJM Interconnection in the eastern U.S., adjacent to New York State, over four years.

Figure S2 shows the results of an optimization study that indicates the potential for bundling WWS resources to match contemporary California power demand with California WWS supply. It shows that combining wind (variable), solar PV (variable), concentrated solar power (CSP, or solar thermal) (variable) with some storage (dispatchable), geothermal (baseload), and hydroelectric (dispatchable within seconds) together, allowed for the matching of hourly power demand (including transmission and distribution losses) with supply on two days in California in 2005. Although results for only two days are shown, results for all hours of all 730 days of 2005 and 2006 indicated that 99.8% of delivered electricity during these days could be produced carbon-free from WWS (Hart and Jacobson, 2011). The analysis accounted for long periods of low wind and solar energy simultaneously; thus, it accounted for both long- and short-term variability of WWS resources.

For that study, the geothermal power installed was increased over 2005 levels but was limited by California's geothermal resources. The daily hydroelectric generation was determined by estimating the historical generation on those days from reservoir discharge data. Wind and solar capacities were increased substantially over current levels, but did not exceed maximum levels determined by prior land and resource availability studies (cited in Hart and Jacobson, 2011). Natural gas was held as reserve backup (grey in the figures) and provided energy for the few remaining hours.

Eliminating the remaining few hours where natural gas reserves were used in the

California study requires additional measures discussed in Section S3.B onward. These include the use of demand-response grid management, additional storage with CSP and other storage technologies, electric vehicle charging and management, and increases in wind and solar capacities beyond those used in the study. In the last case, if more electric power than needed for the grid were generated, it would be used to produce city heat for air and water and to produce hydrogen for building heat, high-temperature industrial processes, and transportation. Implementing these sorts of measures should eliminate the need for natural gas in a 100% (all-sectors) WWS world.

Figure S2. Matching California electricity demand plus transmission/distribution losses (black line) with 100% renewable supply based on a least-cost optimization calculation for two days in 2005.
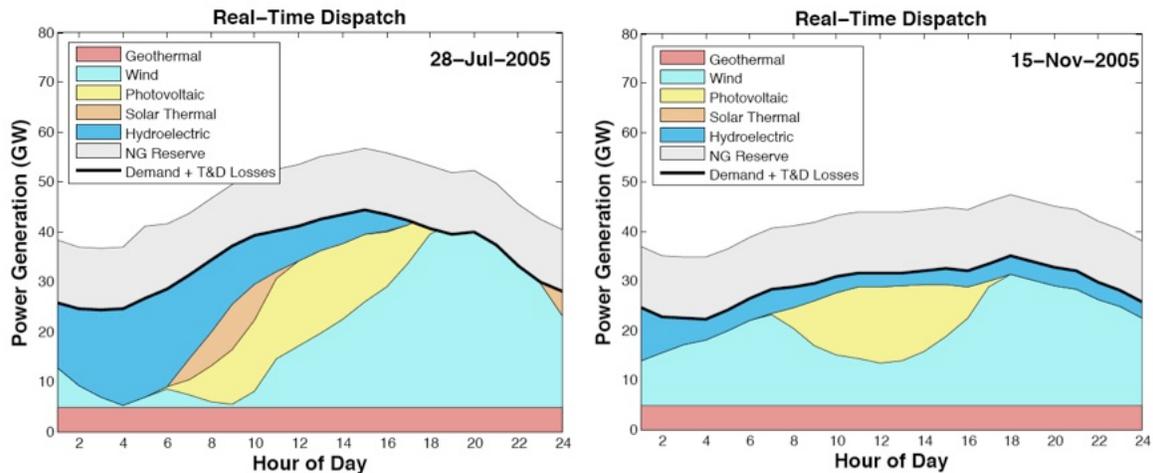
Notes: System capacities are 73.5 GW of wind, 26.4 GW of CSP, 28.2 GW of photovoltaics, 4.8 GW of geothermal, 20.8 GW of hydroelectric, and 24.8 GW of natural gas. Transmission and distribution losses are 7% of the demand. The least-cost optimization accounts for the day-ahead forecast of hourly resources, carbon emissions, wind curtailment, and 8-hour thermal storage at CSP facilities, allowing for the nighttime production of energy by CSP. The hydroelectric supply is based on historical reservoir discharge data and currently imported generation from the Pacific Northwest. The wind and solar supplies were obtained by aggregating hourly wind and solar power at several sites in California estimated from wind speed and solar irradiance data for those hours applied to a specific turbine power curve, a specific concentrated solar plant configuration (parabolic trough collectors on single-axis trackers), and specific rooftop PV characteristics. The geothermal

supply was increased over 2005 but limited by California's developable resources. Natural gas capacity (grey) is a reserve for backup when needed and was not actually needed during the two simulation days. Source: Hart and Jacobson (2011).

S3.B. Using Demand-Response Grid Management to Adjust Demand to Supply

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

S3.C. Oversizing WWS to Match Demand Better and Provide Hydrogen and District Heat

Oversizing the peak capacity of wind and solar installations to exceed peak inflexible power demand can reduce the time that available WWS power supply is below demand, thereby reducing the need for other measures to meet demand. The additional energy available when WWS generation exceeds demand can be used to produce district heat for water and air and hydrogen (a storage fuel) for heating and transportation. Hydrogen must be produced in any case as part of the WWS solution.

Hydrogen for transportation can be produced at vehicle fueling stations by transmitting the excess electric power directly to those stations by existing or expanded transmission. The alternative is to produce hydrogen at a central location, then transfer it by pipeline to fueling stations. However, transmission via electricity can use more of the existing infrastructure. Denmark currently uses excess wind energy for district heating using heat pumps and thermal stores (e.g., Elsman, 2009).

Oversizing and using excess energy for hydrogen and district heating would also eliminate the current practice of shutting down (curtailing) wind and solar resources when they produce more energy than the grid can accommodate. Curtailing wastes energy; thus, reducing curtailment and using the energy for other purposes should reduce overall system costs.

Whereas installing additional WWS generators to oversize the grid requires additional capital cost, that cost may be balanced by the sale of electricity at peak prices (e.g., generators would produce additional electricity at times of peak demand), the sale of electricity for city heat and hydrogen production, and the elimination of lost income upon eliminating curtailment. The least-cost combination of total system capacity, location and

mix of generators, demand management, hydrogen production and storage, and other supply-demand matching methods is an optimization problem that to our knowledge has not yet been fully analyzed for a 100% WWS system supplying all energy sectors.

S3.D. Using Weather Forecasts to Plan for and Reduce Backup Requirements

Forecasting the weather (winds, sunlight, waves, tides, and precipitation) reduces the cost of the grid integration of WWS by improving the ability of grid operators to appropriately schedule backup power for when a variable energy source might produce less than anticipated. Under the current infrastructure, good forecast accuracy can also reduce the use of fossil-fuel peaker plants, which can be rapidly turned on and ramped to meet demand, but which emit more pollution during transient operation. Good forecasting can also reduce inefficient part-loading of plants to provide spinning reserves, thereby reducing the overall carbon emissions of the system compared with using natural gas as backup (Hart and Jacobson, 2011; 2012).

The California plan proposed here uses hydroelectric and stored CSP, but not natural gas, to fill in gaps in electric power supply. Better forecasting will improve the use of hydroelectric resources. Forecasting is done with both numerical weather prediction models, the best of which can produce usable predictions 1 to 4 days in advance, and with statistical models based on local measurements and historical behavior. The use of forecasting reduces uncertainty and makes scheduling more dependable, thus reducing the need for contingent generation capacity, greater storage, or more load shifting.

S3.E. Storing Electric Power

Another method of helping to match power demand with supply is to store excess energy at the site of generation, in a thermal storage medium (as is done with CSP), hydrogen, batteries, pumped hydroelectric power, compressed air (e.g., in underground caverns or turbine nacelles), flywheels, or soil. Storage in hydrogen is particularly advantageous because significant hydrogen will be needed in a global WWS energy economy for use in fuel cells, aircraft, and high-temperature industrial processes. Hydrogen would be produced by electrolysis where the electricity originates from wind and solar when their supply exceeds their demand. In addition, storing energy for use in buildings more efficiently has the potential to reduce building energy use, transmission infrastructure needs, and energy-system costs further. Some methods of improving energy use and storage in buildings include (1) extracting heat in the summer and cold in the winter from the air and solar devices and storing it in the soil for use in the opposite season, (2) recovering heat from air conditioning systems and using it to heat water or air in the same or other buildings, (3) extracting heat (or cold) from the ground, air, or water with heat pumps and using it immediately to heat (or cool) air or water, and (4) using solar energy to generate electricity through PV panels, to recover heat from water used to cool the panels, and to heat water directly for domestic use (e.g., Tolmie et al., 2012; Drake Landing, 2012).

S3.F. Storing Electric Power in Electric Vehicle Batteries

An additional method of better matching power supply with demand is to store electric power in the batteries of BEVs, and then to withdraw such power when needed to supply electricity back to the grid. This concept is referred to as vehicle-to-grid (V2G) (Kempton and Tomic, 2005a). The utility would enter into a contract with each BEV owner to allow

electricity transfers back to the grid any time during a specified period agreed upon by the owner in exchange for a lower electricity price. V2G has the potential to wear down batteries faster, but one study suggests that only 3.2 percent of U.S. light-duty vehicles, if all converted to BEVs, would need to be under contract for V2G vehicles to smooth out U.S. electricity demand if 50 percent of demand were supplied by wind (Kempton and Tomic, 2005b).

S4. Additional Cost Information

Table 3 of the main text presents 2013 and 2030 estimates of fully annualized costs of electric power generation for WWS technologies assuming standard (but not extra-long-distance) transmission and excluding distribution. As indicated in footnote g to Table 3, the calculation of solar PV costs is based on the method and assumptions presented in Table A.1d of Delucchi and Jacobson (2011), but with the following adjustments:

1) The low-cost \$/kWh estimates in Table 3 are based on the U.S. Department of Energy's "SunShot" total-system capital-cost targets of \$1000/kW$_{DC}$ for utility-scale fixed-axis PV, \$1250/kW$_{DC}$ for commercial rooftop PV, and \$1500/kW$_{DC}$ for residential rooftop PV for the year 2020 (DOE, 2012); the high-cost estimates are based on Goodrich et al.'s (2012) detailed total-system capital-cost estimates of \$1710/kW$_{DC}$ for utility-scale fixed-axis PV, \$1990/kW$_{DC}$ for commercial rooftop PV, and \$2290/kW$_{DC}$ for residential rooftop PV in 2020, only "evolutionary" progress from 2010 to 2020.

2) The inverter cost is subtracted from the total system cost above and estimated separately assuming that the inverter is 12.3% (residential), 10.0% (commercial), or 9.3% (utility) of total system capital cost (derived from the analysis of Goodrich et al., 2012), and that the inverter lifetime is 14 years (based on manufacturer statements, cited in Navigant Consulting [2006], that an inverter lifetime of 15 years is achievable).

3) The capacity factor (CF) is the ratio of year-round average AC electrical power to the maximum rated DC power capacity (AC_{ave}/DC_{cap}) (DOE, 2012). It thus accounts for the variability and availability of solar insolation, the DC-to-AC efficiency of the system (governed mainly by the performance of the inverter), and other system losses. Because technological progress is likely to improve the inverter and other non-module components, it is useful to treat the overall CF as the product of two factors: 1) the ratio of year-round average DC power from the module to the maximum rated DC power capacity (DC_{ave}/DC_{cap}), and 2) the ratio of year-round average AC power out of the system to the year-round average DC power from the module (AC_{ave}/DC_{ave}), where the second factor comprises components subject to technological improvements over time.

For any given technology, the overall CF also degrades slightly over time as the major components slowly deteriorate. To estimate a lifetime-average CF (CF_{life}) we multiply a year-zero CF (CF_0) by a lifetime average degradation factor (DF). Thus, for any given technology or year of deployment:

$CF_{life} = CF_0$ x DF = $(DC_{ave}/DC_{cap})_0$ x $(AC_{ave}/DC_{ave})_0$ x DF.

The lifetime average degradation factor depends on the PV technology, system maintenance, and other factors. A detailed review by Jordan and Kurtz (2013) indicates that current large-scale PV systems degrade at about 0.4%/year over their lifetime. Jordan and Kurtz (2013) show that the degradation rate has been declining with time, so we assume that the rate declines by 0.7% per year (in relative terms). We assume 10% higher values for commercial/government PV and 15% higher for residential PV. We assume that the lifetime average factor is obtained at year 20.

Using the National Renewable Energy Laboratory's PVWATTS calculator (NREL, 2013), we estimate that the year-zero ratio of AC to DC output $(AC_{ave}/DC_{ave})_0$, accounting for losses in the inverter, wiring, and performance of the system, can range from 75% to 93% for utility-scale PV. We assume a value of 84% for 2012, and that improvement in technology and operations reduce the loss (16% in 2012) by 1% per year (in relative terms). We also assume that $(AC_{ave}/DC_{ave})_0$ is 5% lower (in relative terms) for commercial rooftop systems and 10% lower for rooftop PV systems.

We calculate the factor $(DC_{ave}/DC_{cap})_0$ as $CF_0/(AC_{ave}/DC_{ave})_0$, where our assumptions for CF_0 are as follows:

System	CF_0	Notes
Residential PV	18.0%	Lopez et al. (2012) estimate 16% for California rooftop PV. However, Energy and Environmental Economics (2013, Figure 3) report slightly higher capacity factors based on actual meter data for rooftop PV in California. We assume that year-zero factors are slightly higher still than reported in-

use factors.

Comm./govt. PV	19.0%	Assume slightly higher than residential rooftop PV because of better siting and maintenance.
Utility PV	26.0%	Figure A-2 of DOE (2012) shows that capacity factors for utility-scale central PV in California range from 24% to above 26%, with the major desert areas above 26%.

We assume that the resultant calculated factor $(DC_{ave}/DC_{cap})_0$ is the same in 2050 as in 2012; that is, we assume that there is no systematic change in solar availability, orientation, shading, and so on from 2012 to 2050.

CFs are used in the calculations of Table 2 as well as in the cost calculations of Table 3. Table 2 estimates pertain to the WWS stock in place in the year 2050. Table 3 estimates pertain to new WWS technologies installed in 2030. For Table 2, we assume that the average technology in place in 2050 was installed in the year 2035. Table S1 provides the assumptions and results for solar PV CFs.

Table S1. Assumptions and results for solar PV capacity factors.

Capacity factor in year zero (CF_0)	2012	2030	2035
Residential	18.0%	n.a.	n.a.
Commercial/government PV	19.0%	n.a.	n.a.
Utility PV	26.0%	n.a.	n.a.
$(dc_{ave}/dc_{cap})_0$	2012	2030	2035
Residential PV	23%	23%	23%
Commercial/government PV	24%	24%	24%

	2012	2030	2035
Utility PV	31%	31%	31%
$(ac_{ave}/dc_{ave})_0$	**2012**	**2030**	**2035**
Residential	76%	78%	80%
Commercial/government PV	80%	82%	85%
Utility PV	84%	87%	89%
Degradation factor (%/year)	**2012**	**2030**	**2035**
Residential	0.46%	0.41%	0.34%
Commercial/government PV	0.46%	0.39%	0.33%
Utility PV	0.40%	0.35%	0.30%
Overall degradation factor (DF)	**2012**	**2030**	**2035**
Residential PV	91%	92%	93%
Commercial/government PV	92%	93%	94%
Utility PV	92%	93%	94%
Capacity factor (CF)	**2012**	**2030**	**2035**
Residential PV	16.4%	17.1%	17.9%
Commercial/government PV	17.4%	18.1%	18.9%
Utility PV	24.0%	25.0%	26.1%

Note that for the purpose of calculating the technical potential rooftop PV capacity, we assume that the CF in warmer areas of California is 1% higher than the state average, and that the CF in cooler areas is 3% lower.

4) The lifetime of utility-scale PV is 40 years (high-cost case) or 50 years (low-cost case) based on Jordan and Kurtz (2013). We assume that the lifetime is 5% less than this for commercial PV and 10% less for residential rooftop PV.

5) The largest component of fixed O&M cost is inverter replacement, which we treat separately, so we reduce fixed O&M from about $10/kW/yr. to $3/kW/yr. for commercial and utility PV and $1.50/kW/yr for residential PV.

6) We assume that $1/3^{rd}$ of residential PV rooftop systems are financed at the same interest rate charged to commercial and utility PV systems, and that the remaining two-thirds of residential PV rooftop systems are bought with cash that has an interest opportunity cost three percentage points less than commercial/utility interest rate. (For the past 20 years, rates on short-term [1-month or 6-month] CDs have been about three percentage points less than the prime rate charged by banks on short-term loans to business and the yield on AAA-rated seasoned corporate bonds [Federal Reserve, 2013]).

7) We add $0.002/kWh to residential and commercial rooftop PV costs to account for local distribution system upgrades.

8) All year-2010 cost figures in Goodrich et al. (2012) and DOE (2012) are converted to year-2007 using GDP implicit price deflators.

Table 3 of the main text shows California's 2011 delivered business (private) plus externality (social) unsubsidized cost of non-WWS conventional fuels (nuclear, coal, and natural gas) for electricity generation. This cost was derived as follows. Lazard (2013) estimates the 2013 levelized cost of energy (LCOE) for nuclear, coal, and natural gas as 10.4, 10.5, and 7.5 U.S. ¢/kWh, respectively. EIA (2012) similarly estimates the 2015

LCOEs for these generators as 111.4, 97.7, and 66.1 ¢/kWh, respectively. Summing the product of the 2013 electric power generation (TWh) in California from nuclear, coal, and gas with the minimum of the Lazard (2013) and EIA (2012) LCOEs for each respective generator, over all generators, then dividing the result by the sum of state power produced by the generators and adding 1 ¢/kWh for transmission gives the Table 3 low estimate of the blended private LCOE of 2013 conventional generation. The same approach is taken to calculate the high value. Assuming the 2.85% rise in California electricity price from 2000 to 2012 (man text) continues gives the 2030 estimated conventional fuel private LCOE in Table 3.

Table S2 breaks down the externality (social) costs of fossil-fuel electric generation in Table 3, including the costs of air pollution morbidity and mortality and global warming damage (e.g. coastline loss, agricultural and fishery losses, human heat stress mortality and increases in severe weather).

Table S2. Mean (and range) of environmental externality costs of electricity generation from coal and natural gas (NG) (business as usual – BAU) and renewables in the U.S. in 2007 (U.S. ¢/kWh).

	2005			2030		
	Air Pollution	Climate	Total	Air Pollution	Climate	Total
Coal	3.2	3.0	6.2 (1.2-22)	1.7	4.8	6.5 (3.3-18)
Natural ga[g] (NG)	0.16	2.7	2.9 (0.5-8.6)[a]	0.13	4.5	4.6 (0.9-8.9)[a]
Coal/NG mix	2.4	2.9	5.3 (1.0-18)	1.1	4.6	5.7 (2.7-15)
Wind, water, sun	<0.01	<0.01	<0.02	<0.01	<0.01	<0.02

Source: Delucchi and Jacobson (2011) but modified for mean shale and conventional natural gas carbon equivalent emissions from Howarth et al. (2011) assuming a current shale: conventional NG mix today of 30:70 and 50:50 in 2030 and a coal/NG mix of 73%/27% in 2005 and 60%/40% in 2030. The estimates do not include costs to worker health and the environment due to the extraction of fossil fuels from the ground, or water pollution costs from natural gas mining and current energy generation. Climate costs are based on a 100-year time frame. For a 20-year time frame, the NG climate costs are about 1.6 times those of coal for the given shale:conventional gas mixes.

[a]McCubbin and Sovacool (2013) estimate slightly higher air pollution-plus-climate-change costs for natural-gas fired power plants in California: 1.4 to 9.5 U.S. ¢/kWh for 1987-2006, and 1.8 to 11.8 U.S. ¢/kWh projected for 2012-2031 (2010 dollars).

The estimates in Table 3 of the main text include the cost of current average-distance transmission. However, many future wind and solar farms may be far from population centers, requiring extra-long-distance transmission. For long-distance transmission, high-voltage direct-current (HVDC) lines are used because they result in lower transmission line losses per unit distance than alternating-current (AC) lines. The cost of extra-long-distance HVDC transmission on land (1200-2000 km) ranges from 0.3-3 U.S. ¢/kWh, with a median estimate of ~1 U.S. cent/kWh (Delucchi and Jacobson, 2011). A system with up to 25% undersea transmission would increase the additional long-distance transmission cost by less than 20%. Transmission needs and costs can be reduced by considering that decreasing transmission capacity among interconnected wind farms by 20% reduces aggregate power by only 1.6% (Archer and Jacobson, 2007). The main barrier to long distance transmission is not cost, but local opposition to the siting of lines and decisions about who will pay the costs. These issues must be addressed during the planning process.

Additional transmission costs can also be minimized by increasing transmission capacity along existing pathways. Methods of increasing transmission capacity without requiring additional rights-of-way or increasing the footprint of transmission lines include the use of dynamic line rating equipment; high-temperature, low-sag conductors; voltage up-rating; and flexible AC transmission systems (e.g., Holman, 2011). To the extent existing pathways need to be expanded or new transmission pathways are required, they will be governed by existing regulatory guidelines.

S5. Additional Air Pollution and Global Warming Damage Reduction Information

Table S3 shows low, medium, and high estimates of premature mortality per year in California due to $PM_{2.5}$ and ozone for the years 2010-2012, from the bottom-up approach

discussed in Section 8.A of the main text. The mortality rates for the state as a whole were ~10,000 (2,600-19,400) premature mortalities/yr for $PM_{2.5}$ and ~2,500 (1,300-3,800) premature mortalities/yr for ozone, giving an overall bottom-up estimate of ~12,500 (3,800-23,200) premature mortalities/year for $PM_{2.5}$ plus O_3.

Table S3. California county 2010-2012 annually-averaged, daily-averaged $PM_{2.5}$ concentration; maximum 8-hour ozone level over the three-year period in the county; 2012 population; and annual premature mortalities/yr.

County	$PM_{2.5}$ ($\mu g/m^3$)	O_3 (ppbv)	Population (2012)	Annually-Averaged Mortalities from $PM_{2.5}$ and O_3					
				Low Estimate		Medium Estimate		High Estimate	
				$PM_{2.5}$	O_3	$PM_{2.5}$	O_3	$PM_{2.5}$	O_3
Alameda	9.1	36.8	1,554,720	52.9	18.9	209	37.8	411	56.5
Alpine	n/a	n/a	1,129	0.0	0.0	0.0	0.0	0.0	0.0
Amador	n/a	41.8	37,035	0.2	0.8	0.7	1.6	1.3	2.4
Butte	10.0	47.8	221,539	9.8	6.6	38.2	13.1	73.8	19.7
Calaveras	7.9	44.2	44,742	1.1	1.1	4.4	2.3	8.6	3.4
Colusa	7.8	38.0	21,411	0.6	0.3	2.3	0.6	4.4	0.9
Contra Costa	7.6	37.9	1,079,597	29.5	15.8	115.9	31.5	227.1	47.1
Del Norte	3.0	n/a	28,290	0.2	0.1	0.7	0.1	1.4	0.2
El Dorado	2.5	55.1	180,561	1.0	8.1	3.9	16.1	7.7	24.1
Fresno	16.0	52.0	947,895	82.5	39.6	318.0	78.9	610.9	117.9
Glenn	n/a	41.2	27,992	0.1	0.5	0.5	1.0	1.0	1.6
Humboldt	7.5	30.0	134,827	3.4	0.4	13.6	0.9	26.9	1.3
Imperial	13.1	48.1	176,948	11.0	5.7	43.2	11.3	84.2	16.9
Inyo	7.5	49.2	18,495	0.5	0.6	2.0	1.2	3.9	1.8
Kern	40.1	66.9	856,158	239	62.3	908	124	1697	185
Kings	17.5	52.0	151,364	14.7	6.3	57.3	12.5	110.7	18.7
Lake	3.5	36.6	63,983	0.5	0.7	2.0	1.3	4.0	2.0
Lassen	n/a	n/a	33,658	0.2	0.1	0.6	0.2	1.2	0.2
Los Angeles	15.4	54.5	9,962,789	794	441	3113	878	6067	1311
Madera	18.5	52.8	152,218	15.8	6.2	61.7	12.3	119.2	18.4
Marin	9.6	28.4	256,069	9.2	0.7	36.2	1.5	71.2	2.2
Mariposa	3.2	60.1	17,905	0.1	1.0	0.5	2.0	1.0	3.0

Mendocino	8.4	26.5	87,428	2.4	0.2	9.5	0.4	18.7	0.6
Merced	13.9	47.2	262,305	18.0	8.5	70.4	16.9	136.6	25.2
Modoc	n/a	n/a	9,327	0.0	0.0	0.2	0.0	0.3	0.1
Mono	2.2	n/a	14,348	0.1	0.0	0.3	0.1	0.5	0.1
Monterey	6.0	35.4	426,762	7.1	3.3	28.0	6.5	55.5	9.8
Napa	9.8	34.5	139,045	5.3	1.1	20.9	2.3	41.1	3.4
Nevada	5.9	55.1	98,292	1.5	4.4	6.1	8.8	12.0	13.1
Orange	12.9	43.3	3,090,132	186	67.2	731	134	1431	201
Placer	7.2	46.1	361,682	8.7	10.7	34.4	21.2	67.6	31.7
Plumas	12.1	n/a	19,399	1.2	0.0	4.6	0.1	9.0	0.1
Riverside	18.3	57.7	2,268,783	233	114	911	227	1766	338
Sacramento	9.5	46.9	1,450,121	58.0	45.1	227	89.7	442	134
San Benito	5.5	44.0	56,884	0.8	1.2	3.3	2.4	6.4	3.6
San Bernardino	20.0	59.6	2,081,313	241	113	941	225.5	1821	337
San Diego	12.5	51.2	3,177,063	180	116	710	231	1393	346
San Francisco	9.4	28.6	825,863	30.8	2.2	121.3	4.4	238.0	6.6
San Joaquin	12.2	43.8	702,612	40.2	17.4	157.3	34.7	305.8	51.9
San Luis Obispo	10.6	50.1	274,804	12.0	9.3	47.4	18.5	93.0	27.7
San Mateo	8.5	29.4	739,311	22.5	2.9	88.9	5.8	174.9	8.7
Santa Barbara	9.8	44.2	431,249	15.7	8.9	62.0	17.8	122.3	26.7
Santa Clara	10.1	40.5	1,837,504	75.2	30.3	296.0	60.4	580.1	90.4
Santa Cruz	6.2	36.9	266,776	4.3	2.4	17.1	4.9	33.9	7.3
Shasta	5.3	47.5	178,586	2.7	5.0	10.6	10.0	20.9	15.0
Sierra	n/a	n/a	3,086	0.0	0.0	0.1	0.0	0.1	0.0
Siskiyou	5.3	36.9	44,154	0.7	0.6	2.7	1.1	5.3	1.7
Solano	8.9	38.4	420,757	14.6	5.2	57.4	10.4	112.5	15.5
Sonoma	8.0	32.8	491,829	13.9	2.6	55.1	5.1	109	7.7
Stanislaus	15.1	46.2	521,726	41.7	16.5	162	32.8	312	49.0
Sutter	7.0	50.9	95,022	2.3	3.4	9.2	6.8	18.0	10.2
Tehama	10.2	55.2	63,406	2.6	2.8	10.2	5.7	20.0	8.5
Trinity	6.5	n/a	13,526	0.3	0.0	1.1	0.1	2.1	0.1
Tulare	15.5	54.4	451,977	36.4	20.9	142	41.5	275	62.0
Tuolumne	n/a	45.8	54,008	0.2	1.5	1.0	2.9	1.9	4.4
Ventura	9.3	48.7	835,981	30.6	26.4	121.2	52.5	239	78.6
Yolo	6.5	39.7	204,118	4.4	3.4	17.3	6.9	34.0	10.3
Yuba	n/a	n/a	72,926	0.3	0.2	1.3	0.3	2.6	0.5
TOTAL	--	--	38,041,430	2,562	1,263	10,011	2,516	19,434	3,760

Total PM$_{2.5}$+O$_3$	3,825	12,528	23,194

Premature mortality due to ozone exposure was estimated on the basis of the 8-hr maximum ozone each day over the period 2010-2012 (CARB, 2012a). Relative risks and the ozone-health-risk equation were as in Jacobson (2010). The low ambient concentration threshold for ozone premature mortality was assumed to be 35 ppbv (Jacobson, 2010 and reference therein). Mortality due to PM$_{2.5}$ exposure was estimated on the basis of daily-averaged PM$_{2.5}$ over the period 2010-2012 (CARB, 2012a) and the relative risks for long-term health impacts PM$_{2.5}$ (Pope et al., 2002) applied to all ages as in Lepeule et al. (2012) rather than those over 30 years old as in Pope et al. (2002). The threshold for PM$_{2.5}$ was zero but concentrations below 8 μg/m^3 were down-weighted as in Jacobson (2010). To determine the county-wide mortality rates, individual mortality rates were averaged over each station and the maximum station average mortality rate was used to represent the population within the respective county. For the PM$_{2.5}$ calculations, data were not available for 1% of the population and for the ozone calculations, data were not available for 1% of the population. For these populations, mortality rates were set equal to the minimum county mortality rate for a given state, as determined per the method specified above. In cases where 2012 data were unavailable, data from 2013 were used instead. All mortality rates for 2010-2012 were calculated using 2012 county populations. PM$_{2.5}$ and ozone concentrations in the table above reflect the three-year average concentrations at the representative station(s) within each county. Since mortality rates were first calculated for each data point and then averaged over each station, these average concentrations cannot directly be used to reproduce each county mortality rate. In cases where "n/a" is shown, data within that county were not available (and the minimum county mortality rate within the state was used in these cases, as specified above).

S5.B. Discussion of International Emissions on Global Warming Impacts in California

Section 8 of the main text discussed the U.S. and international air pollution and global warming cost avoidance due to implementing WWS in California, thereby eliminating energy-related emissions in the state. Here, the estimated cost of all international global warming emissions on California is summarized.

Kahrl and Roland-Holst (2008) indicate that, if no action is taken to mitigate global warming, long-term damage (out to about the year 2100) to California could be at least $7.3 to $46.6 billion/yr (in 2006 U.S. dollars), depending on the emission scenario and level of warming (Table S4).

Table S4. Long-term, global warming costs to California if no mitigation actions are taken – damages to different economic sectors in California (2006 U.S. dollars) (Kahrl and Roland-Holst, 2008).

	Damage cost in sector ($ billion/yr.)	
Sector incurring damages	Low Estimate	High Estimate
Water	Id	0.6
Energy	2.7	6.3
Tourism and Recreation	0.2	7.5
Real Estate (Damage from Water)	0.2	1.4
Real Estate (Damage from Fire)	0.1	2.5
Agriculture, Forestry, Fisheries	0.3	4.3
Transportation	Id	Id
Public Health	3.8	24.0
Total all sectors above	7.3	46.6

Id = insufficient data to provide an estimate.

Of particular concern in California is the effect of global warming on water supply. Changing temperatures shift California's hydrological regime, which decreases the availability of water stored in the Sierra snowpack, increases the frequency and severity of drought and floods, increases the probability of levee failure, alters river hydrology, and changes habitat from reduced summer flows. Water shortages are expected to increase the needs for additional water storage and transport. The damage costs of increased flooding and the cost of building additional water-related infrastructure vary considerably across small scales and to our knowledge have not been estimated.

Higher temperatures are also expected to increase costs of energy in California. A decrease in stored water will decrease hydroelectric power and result in additional costs to replace the lost hydroelectricity or to increase storage capacity. Higher temperatures will also increase the use of air conditioning during the summer and increase power outages due to increased winter storm activity. These impacts are included in the "energy sector" costs of Table S4.

Global warming will affect tourism in California related to beaches, skiing, and national parks. Kahrl and Roland-Holst (2008) estimate that long-term damages to the tourism and recreation sector could be $0.2 billion to $7.5 billion per year (Table S4).

Real estate in California is threatened by the increased frequency and severity of wildfires resulting from global warming, especially in the foothills of the Sierra Mountains and the southern coast. Warming-induced damages due to increased wildfire activity are estimated to range from $1.3-4 billion per decade. In addition, $900 billion in residential real estate assets near the coast will be at additional risk due to increased sea level rise and coastal storm activity.

Global warming will damage agriculture in California, resulting in $750 million lost annually. The total damage to commercial agriculture and forestry from pests, pathogens, weeds and resulting control costs will add $2-3 billion/yr (Kahrl and Roland-Holst, 2008; included in the estimates of Table S4).

Finally, the effects of global warming on public health in California are significant. The public health sector is expected to experience an annual increase in costs of $3.8 to $24 billion/yr due to global warming (Table S4) because higher temperatures increase air pollution the most in areas where pollution is already a serious problem.

S6. Impacts of WWS on Jobs and Labor earnings due to New Electric Power Plants

Table 5 of the main text provided the number of construction and operational-period jobs as well as the corresponding revenues from such jobs, for each WWS electric power sector proposed here. Earnings are in the form of wages, local revenue, services, and supply-chain impacts during either the construction or operational period. This section provides more details about JEDI model assumptions and job/earning results for each WWS technology.

S6.A. Onshore and Offshore Wind

Powering 25% of California's 2050 all-purpose energy demand with onshore wind and 10% with offshore wind (Table 2 of the main text) results in the numbers of construction and operational-period jobs and corresponding earnings provided in Table 5, as determined by the JEDI models for wind.

S6.B. Concentrated Solar Power Plant, Solar PV Power Plants, and Rooftop Solar PV

Table 2 proposes generating 55.5% of California's 2050 total electricity with solar PV on roofs and in power plants and with CSP facilities. Table 5 provides the resulting job and revenue numbers, as determined by the JEDI models for solar.

S6.C. Hydroelectric, Tidal and Wave

Table 2 proposes that California generate 3.5% of its total electric power in 2050 from hydroelectric, 0.5% from tidal, and 0.5% from wave resources. The present plan will require no additional dam construction or corresponding jobs. Instead, it requires an increase in the

capacity factor of existing dams through policy measures. If additional dams were added, 2-3 full-time jobs would be created per MW of hydropower generated (Navigant Consulting, 2009). Temporary construction and other supply chain jobs would be ~6.5 full-time equivalent (FTE) jobs / MW (Navigant Consulting, 2009). FTEs are jobs during the life of the construction phase.

Tidal turbines and wave devices are developing technologies that have little practical implementation at present. Table 2 provides the installed capacities of tidal and wave proposed for California. Assuming the same number of construction and permanent jobs per installed MW as for offshore wind power, Table 5 gives the projected number of jobs and revenues for tidal and wave power installation and operation.

S6.D. Geothermal

California currently has significant geothermal energy infrastructure in place (CEC, 2012a). Table 2 indicates that 7,200 MW additional geothermal capacity is needed by 2050. From the JEDI model for California, 0.48 40-year construction jobs and 0.07 40-year operation jobs result from each MW of installed geothermal power. These data result in the job numbers in Table 5.

The JEDI models are economic input-output models that have several uncertainties (Linowes, 2012). To evaluate the robustness of the models, we compared their results with calculations derived from an aggregation of 15 different renewable energy job creation models (Wei et al., 2010) (Table S5). These included input/output models, such as JEDI, and bottom-up analytical models. Table 5 of the main text suggests that the JEDI models

estimated 190,600 new 40-year operation jobs due to WWS based on meeting 100% of 2050 energy demand for all purposes with WWS in California. This estimate falls within the range of 99,000-506,000 jobs derived from the aggregation of models from Wei et al. (2010), as shown in Table S5.

Table S5. Estimated number of permanent operations and maintenance jobs per installed MW of energy source (assuming the proposed new installed capacities derived from Table 2 of the main text). The range is based on results from an aggregation of models from Wei et al. (2012).

	Jobs per Installed MW		Number of jobs	
			Lower	*Upper*
Onshore wind	0.14	0.4	17,600	50,400
Offshore wind	0.14	0.4	5,500	15,600
Wave device	0.14	0.4	520	1,500
Geothermal plant	1.67	1.78	12,000	12,800
Hydroelectric plant	1.14	1.14	0	0
Tidal turbine	0.14	0.4	470	1,350
Res. roof PV system	0.12	1	9,000	75,000
Com/gov roof PV system	0.12	1	6,400	53,400
Utility solar PV plant	0.12	1	20,700	173,000
Utility CSP plant	0.22	1	27,000	122,600
Total			99,000	506,000

S7. Reducing Energy Use in Buildings, Neighborhoods, and Commercial Complexes

The proposed plan will enhance existing efforts to improve energy efficiency in residential, commercial, institutional, and government buildings to reduce energy demand in California. Current state energy policies promote building efficiency through appliance standards, regulations, tax incentives, education, and renewable energy portfolios. As a result of historic policies, California's per capita electric power demand remained level at ~6500

kWh/person from 1970-2010, whereas U.S. demand increased from 8000 to 12,000 kWh/person during the same period (Rocky Mountain Institute, 2011).

Some of the existing policies that have and will continue to drive efficiency in California include Title 24, Title 20, 2003 Energy Action Plan, AB32, and AB758. These are briefly discussed below.

- Title 24 (part 6) (California Code of Regulations Energy Efficiency Standards for Residential and Nonresidential Buildings) and Title 20 (California's Appliance Efficiency Regulations) have set the stage for energy-efficient building and conservation standards in California. These codes were established in 1976 and 1978, respectively, in response to a legislative mandate to reduce California's energy consumption. The regulations were largely responsible for keeping per capita electricity sales level in California over the last 4 decades (CEC, 2012c).

- California's 2003 Energy Action Plan (California, 2003) identifies necessary actions to eliminate energy outages and excessive price spikes in electricity or natural gas with the goal of providing reasonably-priced and environmentally sound power for Californians. The first action item of the plan focused on conservation and resource efficiency to minimize the need for new power generation (California, 2003).

- AB 32, the Global Warming Solutions Act of 2006, built upon the 2003 Energy Action Plan, setting into law a 2020 greenhouse gas emissions cap that requires carbon-equivalent emissions to be reduced to 1990 levels. The California Air

Resources Board (CARB) developed actions, which took effect in January 2012, to reduce greenhouse gases and meet the 2020 limit (CARB, 2012b).

- AB758 focuses on achieving greater energy savings for existing residential and nonresidential building stock, especially those structures that fall significantly below the efficiency required by Title 24. The planning stage of AB 758 is nearing completion, and in the next stage, statewide rating and upgrade requirements will be developed by the end of 2015. To develop these ratings and requirements, the California Energy Commission will coordinate with the California Public Utilities Commission and will consult with representatives of local governments, construction companies, utilities, finance industries, real estate industries, workforce development groups, small businesses, and other industries (CEC, 2012d).

Several studies have estimated that efficiency measures can reduce energy use in non-transportation sectors by 20 to 30% or more (Table S6). As such, the assumption in Table 1 of a 5-10% California demand reduction upon complete conversion to WWS is conservative. If the achieved demand reduction exceeds 5-10%, then meeting California's energy needs with 100% WWS will be easier to implement.

Table S6. Studies estimating energy-saving potential of efficiency measures in the non-transportation sectors.

Study	Energy Market	% Savings	Savings with respect to	Notes
McKinsey and Co., 2009	U.S. Non-Transportation	26%	2020 projection found in EIA's 2008 AEO	Includes only positive net-present-value energy-saving strategies

Siddiqui, 2009	U.S. Residential, Commercial & Industrial	3%	2020 projection found in EIA's 2008 AEO	"Realistic Achievable Potential" of 33 selected efficiency measures, considering historical results of energy efficiency programs
Siddiqui, 2009	U.S. Residential, Commercial & Industrial	11%	2020 projection found in EIA's 2008 AEO	"Economic Potential" of 33 selected efficiency measures
Farese, 2012	U.S. Residential and Commercial	20%	2030 projection found in EIA's 2010 AEO	Conservative estimate, using current technology, assuming "rebound effect"
Farese, 2012	U.S. Residential and Commercial	80%	2030 projection found in EIA's 2010 AEO	Aggressive estimate includes early-stage technologies and assumes no "rebound effect"
Kavalec, 2012	CA Electricity Consumption (Residential, Commercial, Industrial, Agricultural)	21.5-24%	2022 CA projected electricity consumption if no efficiency measures had been enacted since 1972	Historic (since 1972) and projected savings attributed to previously-enacted or currently-committed programs, efficiency standards and energy price and other market impacts. These savings are incorporated into CEC baseline energy consumption forecasts.
Kavalec, 2012	CA Natural Gas Consumption (Residential, Commercial, Industrial, Agricultural)	30-33%	2022 CA projected natural gas consumption if no efficiency measures had been enacted since 1972	
CEC, 2012b	CA Electricity Consumption (Residential, Commercial, Industrial, Agricultural)	6.8%	2022 forecasts found in 2012 CEC projections (above)	Uncommitted efficiency savings, in addition to savings already included in CEC forecast, above
CEC, 2012b	CA Natural Gas Consumption (Residential, Commercial, Industrial, Agricultural)	3.3%	2022 forecasts found in 2012 CEC projections (above)	Uncommitted efficiency savings, in addition to savings already included in CEC forecast, above

Many emerging technologies can help to improve energy efficiency in California. For the most part, these technologies have not yet been integrated into current building codes. Some such technologies include (Navigant, 2012)

- LED lighting (residential, commercial and street/parking applications)

- Optimized hot/dry climate air conditioning systems

- Evaporative cooling

- Indirect evaporative cooling

- Ductless air conditioning

- Water-cooled heat exchangers for HVAC equipment

- Residential night ventilation cooling

- Heat pump water heaters

- Condensing gas water heaters

- Improved data center design

- Improved air-flow management

- Variable-speed computer room air conditioning (CRAC) compressors

- Advanced lighting controls

- Evaporator fan controller for medium temperature walk-in evaporator systems

- Combined space and water heater

- Advanced HID lighting – pulse start and ceramic metal halide

- Fault detection and diagnostics

- Variable refrigerant flow

- Advanced steam trap systems

- Reduced working temperature for asphalt

- High performance rooftop unit

- Comprehensive commercial HVAC rooftop unit quality maintenance

S8. State Tax Revenue Consideration

The implementation of this plan will likely affect California'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, 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. 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.

As more of California's infrastructure is electrified under the present plan, revenues from the utility tax will increase, although not nearly so much as the fuel tax revenue decrease. Additional lost revenues can be regained by applying a mileage-based road use tax on noncommercial vehicles similar to the highway use tax levied on commercial vehicles in California. This has been considered at the federal level (NFSIFC, 2009) and piloted in Oregon (ODT, 2007).

If conversion to WWS increases jobs and earnings as expected from Section 9, then income tax revenues, which are the single largest revenue source in California (California State Controller's Office, 2013), 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.

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