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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