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# The Intertwined Renewable Energy–Water–Environment (REWE) Nexus Challenges and Opportunities: A Case Study of California

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**Abstract:** In our built environment, societal production of energy and clean water is inextricably linked to the natural resources from which they are derived. Acknowledgement and consideration of the coupling of energy, water, and the environment (the energy–water–environment nexus) will be critical to a sustainable future. This is particularly true as we transition away from historical energy sources (e.g., coal, petroleum, natural gas) and into the widespread adaptation of renewable energy (RE) sources (e.g., solar, wind, geothermal, hydro, bioenergy) as a strategy to decrease greenhouse gas emissions and consequently slow global climate change. This transition is fraught with both challenges and opportunities at the county, state, national, and international levels, as addressing future societal needs with respect to energy and water, and the environment requires recognition of their interdependence and development of new technologies and societal practices. In this study, the focus is on the RE–water–environment (REWE) nexus. In California, the REWE nexus is becoming increasingly important in achieving 100% clean electricity from eligible RE and zero-carbon resources by 2045 and in the face of climate change and population and economic growth. In this context, California's RE deployment and renewable electrical generation, its RE legislative information, REWE nexus, and intertwined REWE nexus challenges and opportunities in California (e.g., administrative–legal, technology development, digitalization, and end-of-life RE waste) are comprehensively discussed to identify the knowledge gaps in this nexus and solutions.

**Keywords:** renewable energy; water; environment; climate change; California

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## 1. Introduction

Reducing reliance on fossil fuels, decreasing pollution, mitigating climate change [1–5], and creating middle-class jobs (i.e., clean energy jobs) require significant investments and endeavors to build a thriving clean energy economy. In recent years, there has been an increasing interest in making transportation cleaner and more efficient, generating electricity from renewable resources, and constructing energy-efficient homes, buildings, and industrial manufacturing processes and plants [5]. In other words, a sustainable future requires reducing or sequestering the carbon emissions from energy sources and paying considerable attention to generating energy from renewable resources [6]. Some of the most available and common renewable energy (RE) technologies include solar (e.g., photovoltaic (PV), concentrating solar power (CSP), and solar thermal heating and cooling), wind, hydro, geothermal, and bio (e.g., biomass, biogas, and biofuels). In addition, ocean power systems that harness energy from waves, tidal currents, tidal range, ocean currents, ocean thermal energy conversion, and salinity gradients are emerging RE systems that have not yet been commercialized, with the exception of tidal barrages [1,7].

California, a western U.S. state with the largest economy in the U.S., is almost rich in energy resources; however, the state is second in total energy consumption. According to the U.S. Energy Information Administration (EIA), California's energy consumption in 2019, was dominated by natural gas use (Figure 1). In 2019, California consumed 17% of the U.S. total jet fuel, 11% of the U.S. total motor gasoline, and 10% of the total U.S. petroleum products. Still, the growth in energy demand in California has been slowed by the state's energy-saving efforts and implementing other technologies, such as RE [8]. According to the California Energy Commission (CEC), California's in-state electric generation in 2019 was dominated by natural gas electric generation (Figure 2). In 2019, the state's renewable and non-renewable electric generation categories accounted for 32.09% and 67.91% of total generation, respectively. However, the state's low-carbon-emitting electric generation categories (nuclear and large hydropower (>30 megawatts (MW)), and renewables, including solar, geothermal, biomass, wind, and small hydropower (≤30 MW)), accounted for 56.68% of total generation [9]. In 2019, being the top U.S. producer of electricity from RE technologies, such as solar, geothermal, and biomass, California was also the second-highest producer of conventional hydropower.

Transmission of electricity itself contributes to losses in electricity that may lead to compensatory power generation and associated greenhouse gas (GHG) emissions. Thus, the development and purchase of local energy generation to meet local consumption needs may minimize losses associated with transmission and lead to significant GHG reductions [10,11]. Despite being the fourth largest U.S. electricity-producing state, California received approximately 28% of its electricity supply from producing facilities outside the state, such as imports from Arizona, Nevada, Oregon, and even non-neighboring states (e.g., Colorado, New Mexico, Texas, Utah, etc.) and Mexico [8]. In a detailed geographical assessment of California energy providers, Hoffacker et al. [11] found that 42.3% of specified power purchases (in megawatt hours (MWh)) in 2017 by load-serving entities in California were out-of-state and that 78.9% of energy generation was purchased beyond their respective service territories (i.e., non-local) [11].

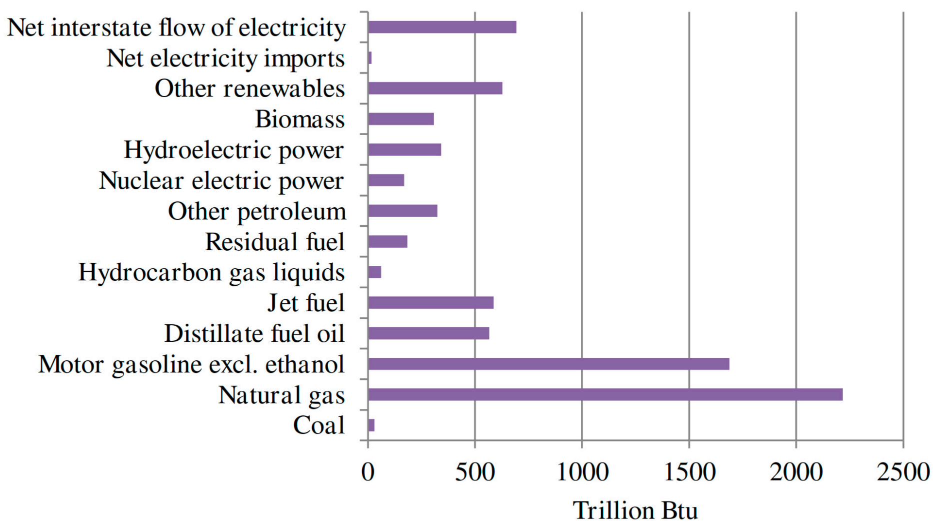


**Figure 1.** California's energy consumption estimates in 2019. Data from the U.S. Energy Information Administration [8].

Producing electricity from renewable resources is one effective strategy to reduce GHG emissions and consequently slow global climate change [12]. Achieving 100% clean electricity (from eligible RE and zero-carbon resources) in California by 2045 while also ensuring affordable and reliable energy is an enormous challenge [13]. Given the magnitude of demand, it is arguable that no state demonstrates the interdependencies of water and energy as demonstrably as the state of California. As in many other states, water is used for energy generation, while energy is essential for water management and use, including extraction, water/wastewater treatment, heating, and distribution [14]. In California, severe drought conditions have characterized the state since at least 2011 and future drought risks are exacerbated by climate change and human water management practices [15–17]. Water will play an integral role in meeting California's climate change purposes and decarbonizing its economy via a transition to complete or one hundred percent clean electricity [14]. Energy development and water availability is also layered over the state's rich environmental history and biodiversity. California comprises 70% of the California Floristic Province; a globally significant biodiversity hotspot where plant richness and species endemism is high (8000 vascular plant species) and threats to its persistence are exceptionally high (only 30% or less of original habitat remains). California's deserts—including the Mojave, Sonoran (or Colorado), Great Basin, and San Joaquin—support high levels of species richness, rarity, and endemism [18,19]. Although desert regions of California have historically faced less anthropogenic threats than coastal regions, deserts are increasingly impacted by both human water management practices and RE development, which may exacerbate increasing threats to desert ecosystems by climate change [20–22].

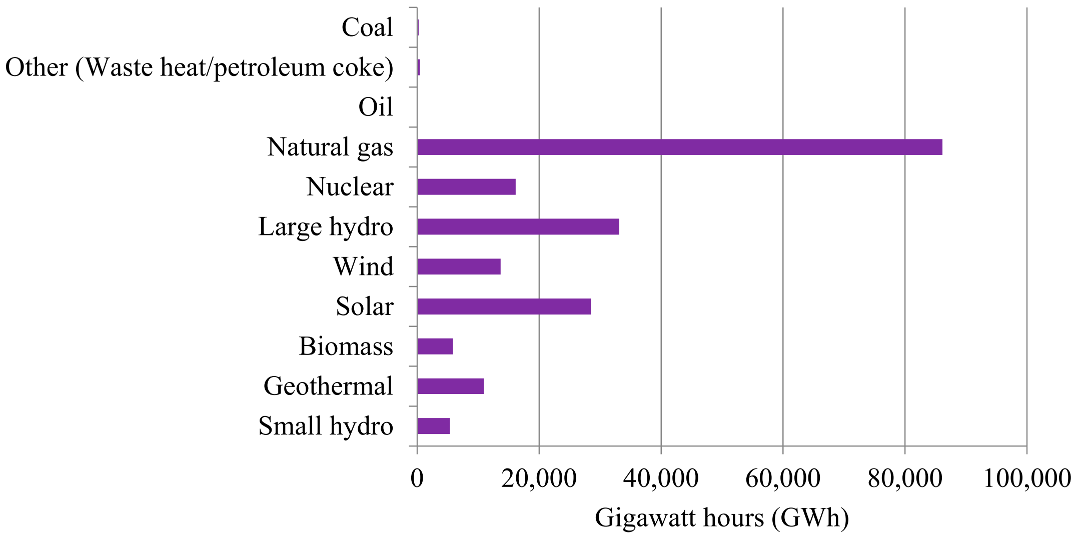


**Figure 2.** California's in-state electric generation by type in 2019. Data from the California Energy Commission [9].

Transition from historical energy sources to RE in California is fraught with both opportunities and challenges in addressing future societal needs with respect to energy and water, and the environment requires recognition of their interdependence and development of new technologies and societal practices. There is a need to comprehensively study the intertwined RE–water–environment (REWE) nexus challenges and opportunities in California and identify the knowledge gaps in this nexus. Thus, this review discusses (i) California's RE deployment and renewable electrical generation, (ii) its RE legislative information, (iii) REWE nexus, and (iv) intertwined REWE nexus challenges and opportunities in California (e.g., administrative–legal, technology development, digitalization, and end-of-life RE waste) to identify the solutions.

## 2. Methodology

A comprehensive literature review concerned with the selected topic was conducted. The rest of the paper is structured as follows: Section 3.1 briefly reviews California's RE legislative information. Section 3.2 discusses RE in California. The REWE nexus is explained in Section 3.3. Section 3.4 summarizes various intertwined REWE nexus challenges and opportunities in California. Finally, conclusions and future outlooks are discussed in Section 4.

## 3. Results and Discussion

### *3.1. California's Renewable Energy Legislative Information*

The RE deployment in California has been promoted by state and federal policies in two waves [23]. The first wave was due to "the Public Utility Regulatory Policies Act of 1978 (PURPA, Public Law 95-617, 92 Stat. 3117, 9 November 1978)" in response to the 1970s energy crisis. It was enacted to promote cogeneration, RE, and competition in generating electricity, as well as electricity conservation [23–25]. The second wave was facilitated by California's "renewable portfolio standard (RPS)", which is one of California's main programs to advance RE [23].

In 2002, California's RPS program was established by "Senate Bill (SB) 1078 (Sher, Renewable energy: California Renewables Portfolio Standard Program, 2001–2002)". This SB required California to generate/procure 20% of its electricity from eligible RE by 2017 [26,27]. The program has been revised several times since then. It was first accelerated in 2006 with "SB 107 (Simitian, Renewable energy: Public Interest Energy Research, Demonstration, and Development Program, 2005–2006)" to mandate that at least 20% of electricity retail sales in California come from eligible RE by 2010 instead of 2017 [28]. In 2011, the program was accelerated with "SB X 1-2 (Simitian, 2011)" that required the enhancement of electricity generated from RE resources so that at least 33% of retail sales in the state per year come from these resources by 2020 [29]. In 2015, "SB 350 (De León, Clean Energy and Pollution Reduction Act of 2015, 2015–2016)" was signed into law, which enhanced the procurement of California's electricity from eligible RE resources from 33% by 2020 to 50% by 2030 [26,30]. In 2018, the program was again advanced with "SB 100 (De León, California Renewables Portfolio Standard Program: emissions of greenhouse gases, 2017–2018)" which increased the RPS to 60% by 2030 and required all California's electricity to come from eligible RE and zero-carbon resources, which do not directly emit climate-altering GHGs during electricity generation, by 2045 [26,31,32].

### *3.2. Renewable Energy in California*

Currently, California produces renewable electricity from solar (solar PV and solar thermal), geothermal, biomass (e.g., landfill gas, municipal solid waste, wood and wood waste, and other biomass fuels), wind, and hydropower. As mentioned above, in 2019, California was the top U.S. producer of electricity from RE technologies such as solar, geothermal, and biomass, the second U.S. producer of electricity from conventional hydropower, and the fifth U.S. producer of electricity from wind energy [8]. According to the CEC, in 2019, the percentages of utility-scale renewable electrical generation (excluding sources smaller than 1 MW) by solar PV, wind, geothermal, biomass, small hydro, and solar thermal were 41%, 21%, 17%, 9%, 8%, and 4%, respectively (Figure 3) [33]. Also, based on data from the CEC regarding the utility-scale renewable electrical generation by county in California for each RE type in 2019 excluding sources smaller than 1 MW (Figure 4), California's solar PV facilities are approximately located throughout the state, Kern county is the state's top producer of electricity from solar PV. However, California's solar thermal facilities are located in San Bernardino and Riverside counties; electricity production from wind is predominantly located in Kern, Solano, Riverside, Alameda, Imperial, San Diego, and Shasta counties, while the state's geothermal power plants are in Sonoma, Imperial, Inyo, Lake, and Mono counties. California has several biomass power plants, and Los Angeles County is the state's top producer of electricity from biomass. Many of California's counties produce electricity from small hydropower, of which Tuolumne is the top producer [34].

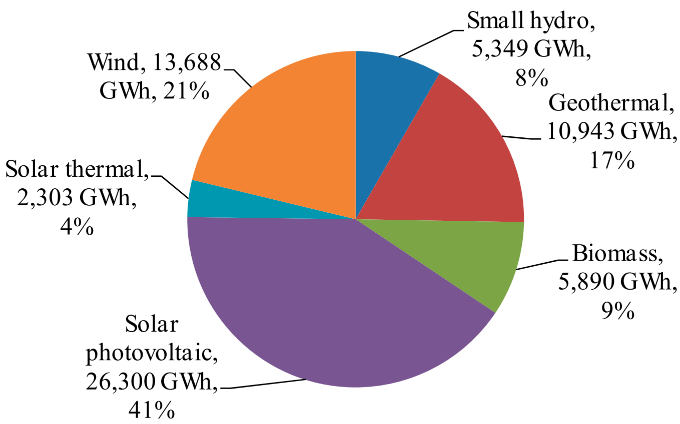


**Figure 3.** Percent and amount of utility-scale renewable electrical generation by RE type in California in 2019. Data from the California Energy Commission [33].

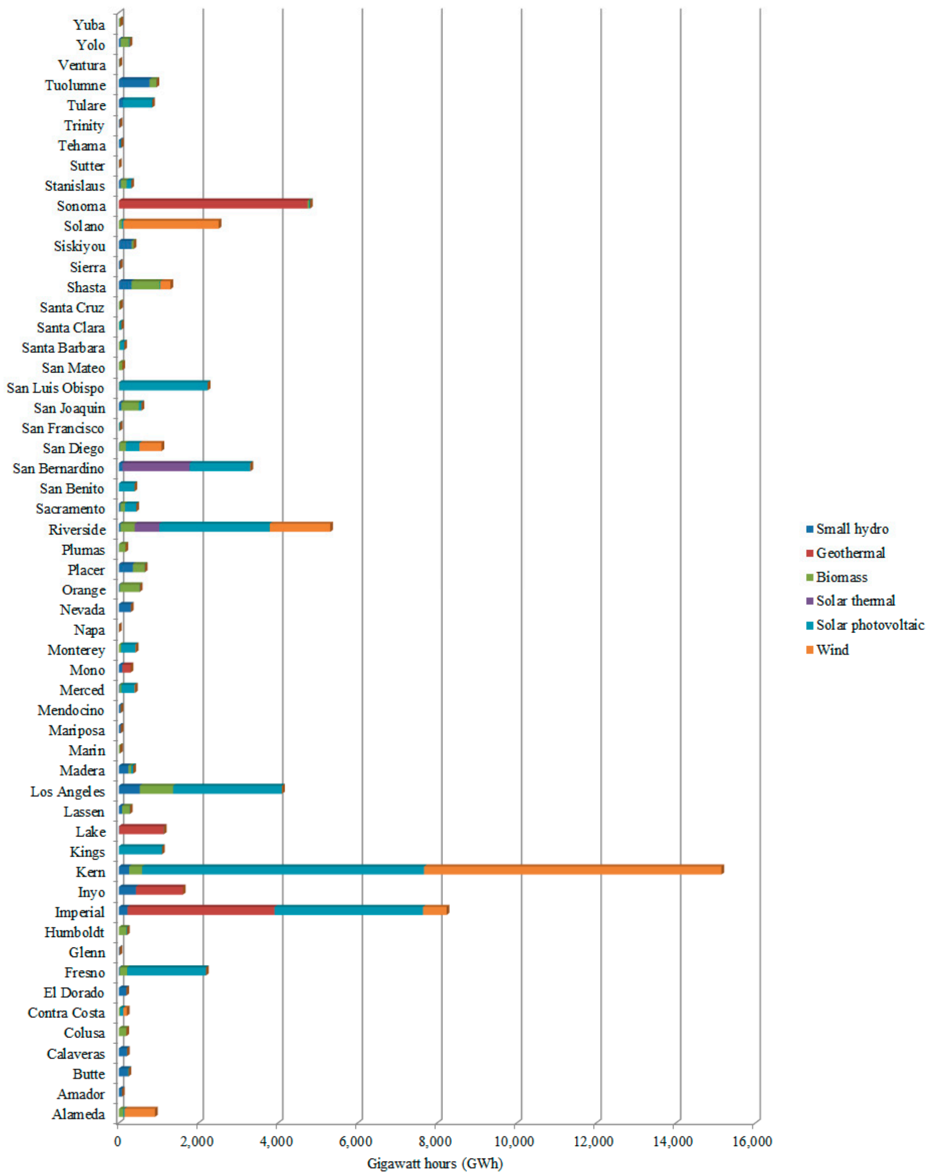


**Figure 4.** Utility-scale renewable electrical generation by county in California for each RE type in 2019. Data from the California Energy Commission [34].

Some of the incentive programs that have contributed to the solar installation growth in California are "California Solar Initiative General Market Program", "Multifamily Affordable Solar Homes", "Single Family Affordable Solar Homes", "New Solar Homes Partnership", "SB1 publicly-owned utility programs", etc. [35].

It is expected that ongoing hydropower generation may be low as long as the drought persists. The state of California is currently planning to partner with the federal government on offshore wind development and to ask the commercial sector for possible rooftop solar and storage. It is necessary to note that RE curtailment has been increasing every year (e.g., 64.5% curtailment increase from 2019 to 2020) due to growth in solar generation and an inability to use all available generated RE. To ensure energy reliability in the state, a diverse mix of resources and technologies, such as battery storage, pumped storage, and demand response, is required [36].

### *3.3. The Renewable Energy–Water–Environment (REWE) Nexus*

In this study, the term "renewable energy (RE)" refers to energy which is produced from natural resources, such as sunlight, wind, rain (hydro), waves, tides, and geothermal heat [2,4,7]. This study focuses primarily on electricity generated from RE. In addition, the word "water" is seen/studied in inter-relationship with RE and the environment; however, it has several applications. Furthermore, the word "environment" refers to both biotic factors (e.g., organisms, their resources, and their interactions) and abiotic factors (e.g., sunlight, air, water, climate, soil, and pollution) that act on an organism, population, and/or ecological community, including processes that affect its development and survival [37,38].

The term REWE nexus describes the interrelationships among RE, water, and the environment, and its understanding can help identify solutions and meet sustainable development goals [39,40]. Some RE generation systems and thermoelectric cooling require water, while water treatment and desalination, wastewater treatment, groundwater pumping, transportation/distribution, water heating, and end-use of water require energy/RE. Also, RE and water are interconnected to the environment. In other words, the environment is the source of both RE and water, and both of these impact on the environment. RE development is connected to the environment throughout the life cycle of a facility. For example, the siting and operating of infrastructural components of the facility itself requires space in an environment (called the 'recipient environment'), which can vary from a commercial rooftop to a seabed substrate supporting a benthic habitat to an undisturbed desert ecosystem [41–43]. Beneficial and negative environmental outcomes owing to RE development have been increasingly documented and include impacts on environmental properties (e.g., land surface temperatures, viewsheds), biodiversity, and ecosystem services [22,44,45]. Space, including in landfills, may also be required at the end-of -life for non-recyclable components and materials from decommissioned RE facilities. In addition, water resources and their conditions can largely impact on organisms in the environment. In developing sustainable policy on REWE nexus, it is essential to consider political or regulatory, economic, social, and technological factors [39,46–48]. In California, the REWE nexus is becoming increasingly important in achieving 100% clean electricity from eligible RE and zero-carbon resources by 2045 and in the face of climate change and population and economic growth [13].

Several studies have reviewed the water–energy nexus [47–51], the water–energy–food nexus [52–58], and the water–energy–food–climate change nexus [59]. In addition, Fayiah et al. [39] have reviewed the most commonly used methods for investigating the water-energy nexus. Furthermore, Vinca et al. [60] have reviewed climate–land–energy-water nexus models. To the best of the authors' knowledge, there is no study on the REWE nexus, particularly for the case of California. In this section, the RE–water nexus, RE–environment nexus, and water–environment nexus in California are reviewed.

#### 3.3.1. The Renewable Energy–Water Nexus

##### Water for Renewable Energy

To assess the water intensity of different RE technologies, one can consider the different stages of the RE supply chain: infrastructure material extraction, manufacturing, and installation; fuel extraction, processing, and transportation; energy transformation (e.g., electricity generation); operation and maintenance; end-use of RE; and end-of-life management of RE infrastructure. Water inputs for RE technologies such as solar, wind, geothermal, tidal, and hydropower during extraction, processing, and transportation steps might be considered negligible [60]. However, bioenergy needs water to produce, process, and transport feedstock. Generally, crop type, local climatic conditions, technology choices, necessity of irrigation, and the irrigation method adopted can affect the water input. Water input may be lowered by developing the processes and systems to boost the water efficiency of common bioenergy generation. Some RE systems, such as geothermal, biomass, and CSP, that utilize thermoelectric generation are water-intensive during operation [60]. The source of water used for cooling (external water or on-site geothermal fluids) and technology can extensively affect water use of geothermal (water consumption of 7600–13,100 L per MWh or higher if on-site geothermal fluids are used for operation) [60–62]. CSP can be water-intensive (up to 4700 L per MWh water consumption) during the operations step, especially where steam turbines are applied [60,63]. Water use can be reduced by as much as 90% when dry cooling systems are used instead [60,64]. Evaporation causes water losses from holding reservoirs in the process of hydropower generation and large hydropower may be very water-intensive if evaporation is accounted for [60,65]. However, the remaining water can be utilized for irrigation, water supply, and recreation, in addition to power generation. There is an interest in applying small hydropower and run-of-the-river systems to avoid a high quantity of water evaporation and the socio-economic impacts related to large hydropower [60].

According to the International Renewable Energy Agency (IRENA), water use and withdrawal can significantly be reduced by deploying RE systems to address the water–energy nexus in several contexts [60]. For instance, in 2013, electricity generation from wind energy in the U.S. led to saving 130 billion liters of water [60]. According to the U.S. Department of Energy (DOE), supplying 20% of U.S. electricity from wind energy by 2030 might diminish cumulative water use in the electric segment by 8% [66].

Currently, thermoelectric, hydropower, and a growing share of RE, especially solar and wind, are California's in-state electric generation categories. Thermoelectric and hydropower (dependent on the water available in rivers and reservoirs, which is vulnerable to California's recent drought and a warming climate) are water-intensive; solar PV and wind energy technologies need relatively little or no water except in their manufacturing. Although some RE systems are water-intensive (e.g., geothermal, biomass, and CSP plants), it is believed that shifting toward RE systems will reduce the energy sector's overall water reliance [67].

##### Renewable Energy for Water

Generally, groundwater pumping, conveyance, water treatment and distribution, wastewater treatment, water heating, and end-use of water require energy [48,67]. RE may be used at different stages of the water supply chain and can reduce the environmental footprint. For example, in recent years, RE has been utilized for water pumping (e.g., solar-based pumping), desalination (e.g., integrating solar and wind resources with various desalination systems, such as reverse osmosis, electrodialysis, etc.), and heating (e.g., geothermal and solar water heating systems), among other uses [60].

Approximately 20% of California's electricity is used by the state's water sector, and its needs are growing [67,68]. According to GEI Consultants/Navigant Consulting, Inc. [69] and PPIC [67], California's water sector consumed energy for groundwater pumping (3%), conveyance (4%), water treatment and distribution (3%), wastewater treatment (2%), and water end-uses (industrial (35%), agricultural (2%), commercial (9%), and residential

(42%)) [67,69]. With plans for seawater desalination and increasing water recycling to provide a "drought-proof" water supply, the water sector is becoming a larger energy consumer, surpassing 20% of the state's total electricity needs. To meet California's goal of 100% clean electricity by 2045, the water sector should invest in clean energy [68].

#### 3.3.2. The Renewable Energy–Environment Nexus

The environment is the source of RE [48], and RE technologies also have environmental impacts—both negative and beneficial (beyond GHG emission mitigation)—depending on the specific technology utilized, the geographic location, and other factors. Across all factors, it is likely that RE systems compare significantly favorably to fossil fuels in terms of net beneficial environmental outcomes; however, to our knowledge, no global assessment exists to date across all energy types. A fifty-eight expert participant workshop led by the Electric Power Research Institute identified six research gaps for the RE–environment nexus that may align climate change and sustainability goals. Such themes include: siting, public acceptance, solar–wildlife interactions, wind–wildlife interactions, solar end-of-life, and wind end-of-life [70].

Adverse environmental impacts related to wind energy generation include issues related to public acceptance, turbine-associated noise and shadow flicker, cultural and/or visual disturbances, and impacts on wildlife (especially bats and birds). Adverse environmental impacts associated with solar energy depend on the scale of the system and the technology used (e.g., solar PV and CSP); however, they include land-use and land-cover issues (e.g., habitat loss, loss of corridors), water consumption, impacts on wildlife, and the use of hazardous materials in manufacturing [71]. Hernandez et al. [72] reviewed the environmental impacts of utility-scale solar energy systems, including impacts on biodiversity, water consumption, soils, land-use and land-cover change, and human health, and discussed the permitting and regulatory implications to minimize its adverse impacts [72]. In another work, Hernandez et al. [73] also identified 16 beneficial environmental outcomes—e.g., pollination, animal welfare, carbon sequestration, and water-use efficiency—from strategically engineered solar energy across diverse recipient environments [73]. Depending on the conversion technology (direct steam, flash, or binary) and cooling system (water-cooled and air-cooled) used, geothermal plants can have different environmental impacts [71]. Open-loop geothermal systems have emissions of hydrogen sulfide, carbon dioxide, ammonia, methane, and boron. Also, land use and water consumption (e.g., for cooling and re-injection) are other adverse environmental impacts related to geothermal energy [74]. Dhar et al. [75] reviewed environmental impacts associated with geothermal plants and suitable mitigation and land reclamation strategies [75]. Land-use and land-cover change, water use, and life-cycle global warming emissions are commonly cited environmental impacts associated with producing energy from biomass [71]. River ecosystems both upstream and downstream from a dam can be disrupted by hydropower plants [76]. Flecker et al. [77] reported that simultaneous consideration of different factors, including river flow, river connectivity, sediment transport, fish diversity, and GHG emissions, as well as the geographical scale of planning, are vital to reducing adverse impacts in achieving energy production goals using hydropower [77].

Generally, the use of RE can diminish carbon emissions and reduce air and water pollution in comparison with the use of fossil fuels [60]. Little or no air pollution can be generated by RE technologies such as wind, solar, and hydropower. However, some air pollutants are emitted by biomass and geothermal technologies, but at much lower rates than by most common fuel-fired power plants [76,78]. In other words, in electricity generation from renewables, wind is responsible for only 0.02–0.04, solar 0.07–0.2, geothermal 0.1–0.2, and hydropower 0.1–0.5 pounds of carbon dioxide equivalent per kilowatt-hour ($CO_2E$/kWh) on a life-cycle basis [76]. However, biomass can be responsible for an extensive variety of global warming emissions depending on the resource and whether it is sustainably sourced and harvested. Not only do wind and solar PV not pollute water resources, but they also do not strain supplies. However, biomass, geothermal, and CSP require water [76]. According to Petek [79], an estimation shows that from 2009 to 2018, the shift toward renewable electricity sources in California decreased annual emissions by about 30 million metric tons (MMT) of carbon dioxide (approximately 6 MMT from the increase in rooftop solar and 24 MMT from the increase in utility-scale renewables) [79].

#### 3.3.3. The Water–Environment Nexus

As mentioned before, the environment is made up of both biotic (e.g., organisms) and abiotic (e.g., sunlight, soil, air, water, climate, and pollution) elements [37,38,80]. Water is an essential part of the environment and is vital for all known forms of life. The distribution and life history of organisms largely depend on the type and body of water, along with climate and other factors. Changes in water conditions (e.g., flow, salinity, and temperature) can impact organisms that live there. The environment is affected by human activities (e.g., water pollution caused by human activities) [80].

California's water resources (e.g., rivers, lakes, wetlands, vernal pools, estuaries, etc.) play a vital role in the state's diverse ecosystem of plants, animals, fish, birds, and aquatic life [80,81]. The state's freshwater biodiversity remains at risk after four decades of the enactment of main state and federal environmental laws [81]. In the state, water use by the environment, agriculture, and urban sectors is approximately 50, 40, and 10%, respectively; however, these values may vary across regions and between wet and dry years [82]. The average percentage of urban water use is: residential (indoors) (36%); residential (outdoors) (32%); commercial and institutional (indoors) (10%); commercial and institutional (outdoors) (15%); industrial (5%); and energy production (2%). As farms and cities use approximately 50% of the state's available water, they also have the potential to discharge harmful pollutants into waterways [81]. On the other hand, as the state's water system/sector is energy-intensive, it may account for up to 10% of the state's GHG emissions [67].

In 2013, California's water sources included instream environmental (34%), groundwater extraction (20%), reuse and seepage (17%), local projects (9%), federal projects (8%), Colorado project (6%), state project (3%), local imported deliveries (1%), and others (e.g., recycled water, inflow, storage, etc.) (2%) [83]. Population growth and climate change with persistent droughts, increased wildfires, and warmer average temperatures are already creating a challenge of keeping a balance between improving ecosystem health and providing reliable water supplies, flood control, and hydropower [81,84]. California's traditional supplies (i.e., snowmelt-fed reservoirs, rivers, and streams) are depleted by climate change and persistent drought [85,86], and the state is turning to groundwater to meet its water needs. Thus, sustainable groundwater management can play a key role in adapting to climate change and increasing water reliability [85].

According to PPIC [81], developing environmental stewardship plans, ecosystem water budges, reforming environmental permitting, promoting projects with multiple benefits (e.g., investing in healthy watersheds), improving accounting for environmental water, and providing reliable funding for ecosystem stewardship can make environmental water allocations more effective and resilient to a changing climate. On the other hand, it is necessary to integrate climate change into water grid management [81].

### *3.4. Challenges and Opportunities*

The REWE nexus understanding can play a key role in identifying solutions, benefiting the economy, and meeting sustainable development goals [39,40,67] in California. In this regard, challenges that need to be addressed include: administrative–legal challenges, technical and technological challenges, digitalization challenges [87], and challenges associated with end-of-life RE wastes [88–90].

Administrative–legal challenges: A successful move toward 100% clean electricity from eligible RE and zero-carbon resources by 2045 can address climate change, improve public health, advance energy equity, support a clean energy economy and create more clean energy jobs; however, it alone cannot achieve statewide carbon neutrality. To achieve this, coordination among state agencies, local governments, and electric utilities for planning is essential [32]. The REWE nexus requires the integration of RE-, water-, and environment-related policies. Thus, these sectors' regulators/policymakers must expand their relationships and work together to design effective policies; however, California is a pioneer in the issue [91]. It can help reduce energy and GHG emissions associated with end-uses of water and the provision of water/wastewater services, and support cross-sectoral collaborations (e.g., better plan integrated RE, water, and the environment [14], investigate synergies in water processes and power grid management, and decrease the energy technologies' vulnerability to drought and an altering climate) [67].

Technology development: In the water sector, the state of California should reduce hurdles and provide incentives for RE technology investment [68]. It seems that innovative cooling systems for thermoelectric plants to reduce/eliminate the use of water for cooling, novel technologies to reduce water use in biofuels production, sea waves for desalination, advanced reverse osmosis systems for desalination, etc., can be helpful in this issue [87]. Technologies which provide reductions in evaporative water loss in open water storage (reservoir) and transport infrastructure (e.g., canals) are also promising, especially those which are coupled to energy generation, such as surface water PV farming. Additionally, new technologies which improve water re-use metrics for non-drinking water applications, such as grey water reclamation and targeted low-energy water purification for agricultural uses, would reduce demand on centralized water purification facilities.

The water sector's energy and GHG emissions may be reduced through expanding urban water conservation and efficiency efforts, electrifying water heater, use of high efficient groundwater/wastewater pumps, etc. [14].

Grid management is key to California as additional RE electricity generation capacity comes on line in order to properly balance RE electricity supply and demand across the fluctuating consumer demand profile during the day [92]. For instance, the daily pattern of electricity supply and demand has been called the "duck curve" by the California Independent System Operator (CAISO) due to its resemblance to the body of a duck [93,94]. This indicates that a system with a high penetration of RE is difficult to balance and control [94], leading to a large amount of available RE being curtailed, thus not being utilized due to lack of demand and lack of energy storage. In other words, the impacts of the intermittent nature of RE resources such as solar and wind on the existing grid system cannot be ignored [94–96] and need to be managed. Energy storage, building more transmission lines, combining diverse RE resources, demand-side management, and placing value on generator flexibility may enhance grid flexibility and improve the integration of RE resources to provide reliable electricity [94]. Fortunately, California is attempting to use advanced technologies and improved grid practices to accommodate a high penetration of RE electricity [92,94]. Offshore wind, energy storage systems (e.g., batteries, pumped hydro, hydrogen, etc.), hydrogen technologies (as a storage resource or use in fuel cells), and flexible load and other demand-side management systems and plans of action across transportation, buildings, and industry can significantly impact SB 100 planning in California [32].

Digitalization: Digitalization refers to the application of digital technologies [97,98]. In recent years, the following technologies have received considerable attention: modern sensors, smart meters, information and communication technologies, big data and artificial intelligence, the internet of things, etc. [99]. The entire energy value chain (from generation to transport, distribution, supply, and consumption) can be impacted by digitalization. For instance, digitalization can help improve energy efficiency and resilience and integrate higher shares of variable RE by delivering flexible electricity systems that provide demand-side solutions and energy storage [98,99]. In the water sector, it can help optimize water services and improve the efficiency and effectiveness of utilities [100]. In California, digitalization may assist access to information and data available on the environment, water, and RE generation, distribution, and use, to optimize systems/processes [87] and help facilitate coordinated cross-sectoral planning.

Quaranta et al. [101] studied the benefits of digitalization, information, communication, and control (DICC) on the environmental performance of hydropower plants and barriers. They reported that DICC in the hydropower sector could provide environmental and energy benefits [101].

End-of-life RE waste: As constituent materials of RE systems (solar panels, wind turbines, battery storage units, and related equipment) may be toxic to humans and the environment, waste management strategies such as reusing (through parts extraction or refurbishment), recycling, disposal in a landfill, or incineration should be considered in their end-of-life [88–90]. Chowdhury et al. [89] have summarized solar PV panel waste recycling technology, the economic aspects of recycling, future improvements in technology, and policy making [89]. Unfortunately, the economics of PV recycling is currently prohibitively expensive, requiring new recycling process development which reduces costs and/or increases the quality/quantity of recovered materials. To partner on developing consistent approaches to collect and recycle end-of-life solar PV panels, electric vehicle batteries, energy storage batteries, and related equipment, a "Memorandum of Understanding" has been signed by California's "Department of Resources Recycling and Recovery (CalRecycle)", the "Department of Toxic Substances Control (DTSC)", the "California Public Utilities Commission (CPUC)", CEC, and the "California Air Resources Board (CARB)" [90]. From January 2021, California is the first state in the U.S. that has added hazardous waste solar panels to its universal waste program, a move toward promoting solar panel recycling and reusing and keeping them out of landfills [102].

According to Domínguez and Geyer [103], as California leads the solar market in the U.S. (i.e., a higher number of PV installations); thus, the end-of-life management of PV modules in this state is crucial [103]. Trends related to the development of PV modules (e.g., crystalline silicon (c-Si) PV modules, compound PV modules, others) recycling technologies were studied in an IEA report in 2018 [104]. It was reported that a few projects were nearly at the commercial or demonstration stage, while others were still in the laboratory or pilot scale. In the future, it is expected that researchers/scientists can resolve the remaining issues related to developing suitable schemes for PV module recycling technologies and contribute to the end-of-life management of PV modules [104]. It is necessary to note that improved PV module recycling technologies and lower recycling costs can result in more recycled PV modules [105,106].

## 4. Conclusions and Future Perspectives

There have been significant shifts towards the development and adoption of RE technologies to reduce reliance on fossil fuels, decrease pollution, mitigate climate change, and create clean energy jobs.

The study reviewed California's RE deployment and renewable electrical generation, its RE legislative information, REWE nexus, and intertwined REWE nexus challenges and opportunities in California. The REWE nexus understanding can help identify solutions, benefit the economy, and meet sustainable development goals.

The state of California has been at the forefront of the paradigm shift towards the adoption of RE technologies in energy economy as well as managing how the shift to renewables impacts water resources and the environment; the REWE nexus. Moving forward effective management of the increasingly interconnected nature of meeting both energy and water demands while maintaining both the natural and our built environment will be critical to a sustainable society. For instance, reduction in the energy consumption (and undesirable emissions) of the water sector is needed through technological developments in water purification/reuse as well as expansion and normalizing of urban water conservation and efficiency efforts. In addition, innovative cooling systems for thermoelectric plants to reduce/eliminate the use of water for cooling, novel technologies to reduce water use in biofuels production, sea waves for desalination, advanced reverse osmosis systems for desalination, etc., can be helpful in this issue [87]. The management of increasing RE sources and their daily cyclical supply through further development and adoption of grid-scale energy storage technologies, in addition to other emerging technologies, will be critical to grid management. Offshore wind, energy storage technologies, hydrogen technologies [32], and flexible load and other demand-side management systems [32,107,108] and plans of action across transportation, buildings, and industry can significantly impact SB 100 planning [32] (increase in RPS to 60% by 2030 and 100% adoption of RE and zero-carbon resources for meeting California's electricity demand by 2045) in California.

Overall, while California has made great strides, these efforts must continue to be sustained towards meeting not only the goals of SB 100 but also the longer-term goals of complete transition to RE. Also, attention should be paid to the end-of-life RE waste.

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