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Assessing future water resource constraints on thermally based renewable energy resources in California

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HIGHLIGHTS

- Water availability can limit solar thermal and geothermal resource utilization.
- Regional water availability is more important than cooling type for resource utilization.
- Spatially targeted water demand reductions enable increased resource utilization.
- Sustainable water-based limits should factor into in resource expansion planning.

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ABSTRACT

In this study, we investigate the extent to which physical water resource availability constraints can limit the deployment of solar thermal and geothermal-based energy resources under future climate scenarios in California. This is accomplished by (1) calculating the water unconstrained potential capacity for solar thermal and geothermal power plants, (2) estimating the available water supply for supporting the water needs of these plants using four climate model simulations under representative concentration pathway (RCP) 8.5, and (3) determining the supportable capacity from the available water supply based on power plant cooling type. We show that regional water availability can limit the installable capacity of solar thermal resources to a range of 10.9–52.6% of solar thermal potential and geothermal resources to between 17.9% and 100% of geothermal potential, depending on cooling system and regional water demand levels by the year 2050. The limiting factor for installable capacity was driven by whether the locations of solar thermal and geothermal resources were spatially aligned with precipitation patterns, with cooling system type acting as a secondary factor. In regions with high solar thermal and geothermal potential, reducing water demand from other sectors was important for alleviating the water constraints on solar thermal and geothermal capacity and increasing total resource potential. Water conservation policies can therefore support the deployment of renewable energy resources and should be considered in future water and energy resource planning.

1. Introduction

Impacts of conventional fossil fuel energy use on the climate, environment and human health have motivated the accelerated deployment of low-carbon and renewable energy resources. In California, many studies have designed optimal pathways to reach the renewable portfolio standard goals, determining the best mixture of low-carbon and renewable energy resources based on different criteria.

Studies have examined the use of economy-wide technology transformations to meet the desired emissions target by 2050 and used energy modeling to determine cost-effective energy technology investments under a range of policy and technical constraints [1,2]. In these studies, solar thermal and geothermal resources were identified as fulfilling varying roles in contributing to the renewable resource mix based on characteristics such as dispatchability and the use of conventional technologies.

Solar thermal and geothermal power plants are based on Rankine-cycle steam turbine power plant configurations, which carry out heat rejection in the condenser by externally cooling the working fluid. This is accomplished by using recirculating or evaporative water cooling systems, which require significant water inputs to provide the required level of cooling. Alternatively, dry cooling systems utilize air, but at a

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higher cost and lower cooling efficiency. Even with dry cooling, water consumption is not eliminated in steam-turbine based power plants, since facilities use make-up water for the main working fluid loop, onsite facility operations, and for cleaning the solar thermal collectors.

In recent years, the characterization of water use in the energy sector and its implications for energy resources has been a topic of considerable research interest. The U.S. Department of Energy [3] conducted a study in 2014 to identify and quantify interactions between energy and water, especially with regards to power plant cooling, finding that thermoelectric power generation utilized 68 billion gallons per day of water and represented the sector with the largest water withdrawal amounts. The Public Policy Institute of California (PPIC) characterized the interconnections between energy and water use in California in 2016 [4], finding that water end-uses (i.e. water heating, process water pressurization, etc…) comprise 88% of the water-related energy use in the state. The use of energy for water in California was also characterized by Cohen et al. [5], who focused on the costs associated with energy for water pumping in conveyance systems and from groundwater aquifers.

The impacts of drought and climate change on hydropower generation have been examined by Gleick [6] under current conditions concluding that climate change induced drought caused increases in natural gas usage through from 2011 to 2015 and Tarroja [7] under projected future conditions, concluding that hydropower variability reduced the efficiency of electric grid operations. Sanders [8] and Peer [9] have characterized the impact of these interactions on electric grid and water resources by investigated the impact of water prices on power plant water use efficiency [10]. These studies found that water fees can reduce water withdrawals by up to 75% but with the tradeoff of increasing wholesale electricity prices by up to 120%. Similar analyses were performed by DeNooyer for Illinois [11], finding that water fees can incentivize cooling system refits on thermal power plants. Stillwell [12,13] investigated alternative water supplies for thermoelectric power plant cooling and examined the feasibility of low water-use cooling technologies, finding that both strategies resulted in significant water savings for local river basins. Lubega [14] focused on this topic in the context of grid reliability, finding that low water-use cooling systems can improve electric system reliability during heat waves. Cooley [15] has also examined future water needs to support electricity production in the Western United States, with detail into the connections between different energy-sector processes and impacts on systems that provide water resources and maintain water quality. Escriva-Bou [16,17] has also investigated patterns for residential water use and related energy and greenhouse gas emissions in California. Arent [18] examined the implications of high renewable deployment for water use among other environmental metrics such as land and material use, concluding that renewable deployment reduced water use by 50%. Li [19] examined regional water conservation in China from the power generation sector in 2030, highlighting spatial misalignment between water resource availability and water demand. In the broader water-energy nexus scope, studies regarding the optimization of policy have been conducted by Gjorgiev [20]. Many tools for informing the planning of water and energy infrastructure development within this context have also been developed [21,22].

As of 2016, solar thermal and geothermal capacity in California is 1.2 GW and 2.8 GW, respectively [23,24]. As early as 1983, solar thermal facilities were being built in California's Mojave Desert with the Solar Electric Generating Station series of power plants. Solar thermal capacity remained stagnant until 2014, when these power plant types experienced renewed interest due to the Renewable Portfolio Standards. Solar thermal resources represent an important component of a utility's renewable portfolio, as thermal storage can be a cheaper alternative to electrical energy storage. Geothermal capacity in California has also remained relatively constant since 2001, but has recently been experiencing renewed interest due to the dispatchability of this resource in comparison to wind and solar.

While interactions between the water and energy sectors have been examined from a variety of standpoints, previous studies have not quantified how water availability can constrain the deployment of renewable energy resources. The majority of the literature has focused on characterizing the water usage of the energy sector or vice versa, but has not applied water use constraints to inform energy resource planning. In California, most of the solar thermal and geothermal potential is located in the southeastern desert areas. However, these regions tend to be water-limited due to local climate conditions, which can constrain the installable capacity of power plants. This limitation may be exacerbated under climate change depending on future shifts in regional water availability [25,26]. Therefore, this study examines how projected changes in water availability will affect the installable capacity of solar thermal and geothermal resources in California and quantifies the contribution of thermally-based renewables in meeting the state's emissions reduction and renewable utilization goals. Our analysis focuses on constraints due to water availability based on atmospheric forcing. This analysis is not intended to examine perturbations from water rights and policy changes, although the study results have implications for future changes in both domains.

2. Methodology

In each of California's hydrologic regions, we calculated the potential installable capacity of solar thermal and geothermal resources based on energy potential. Using climate model projections, we also calculated the available supply of water by conducting a water balance of each hydrologic region. With the available water supply data, we determined the water-constrained installable capacity for each resource considering the water consumption intensity for solar thermal and geothermal power plants in different cooling system configurations. A general overview of the methodology is presented visually in Fig. 1.

2.1. Calculating water-unconstrained solar thermal and geothermal capacity

For solar thermal, we defined installable capacity as the potential usable capacity of solar thermal resources given practical constraints such as land use. We determined land exclusions by removing areas on which solar thermal power plants cannot be installed. We overlaid the remaining land area with solar insolation potential and parameters for the efficiency and capacity factors of a representative solar thermal power plant to determine the installed capacity. For geothermal, installable capacity refers to the potential usable capacity of these resources given the physical suitability of geographic sites to support hydrothermal systems. For geothermal, we utilized available estimates for hydrothermal capacity availability in California.

2.1.1. Solar thermal land exclusions

This analysis excluded lands under the following categories:

- **U.S. Federal Protected Lands**, which encompass all land areas protected from development by United States federal law. The U.S. Geological Survey (USGS) provides data on federally protected lands, including national parks and landmarks.
- **Unsuitable Land Cover**, which refer to land areas on which solar thermal power plants cannot be built due to the physical unsuitability for construction or the current use of the area. We obtained land cover data from the Multi-Resolution Land Characteristics Consortium for different categories using the 2011 National Land Cover Database (NLCD 2011) [27]. Of the land cover types in the 2011 NLCD, the following are assumed to be unsuitable land areas for constructing solar thermal power plants. Descriptions are from the NLCD documentation. The dataset is presented visually in the Supplemental Information.
    - o Wetlands: Woody Wetlands and Emergent Herbaceous Wetlands