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Analyzing land and water requirements for solar deployment in the Southwestern United States

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ABSTRACT

Among the types of renewable energy, solar energy is rapidly gaining popularity. Advances in technology have contributed to improved efficiency and reduced costs for solar energy systems, which can be placed in two categories: concentrated solar power (CSP) and solar photovoltaics (PV). Both types have to use water to clean the mirrors/panels to maintain their efficiency. CSP technology has additional water requirements for wet-cooling, dry-cooling, and hybrid cooling methods. For utility-scale solar deployment, water is also required during solar plant construction and dismantling. The southwest U.S. possesses abundant solar potential, but the expansion of solar power may be restricted by the limited availability of water. Estimates were gathered for water and land use for solar systems and harmonized through review and screening of relevant literature. Next, the estimates were incorporated into a system dynamics model to analyze water availability and usage, land availability and usage, and associated reductions in carbon emissions for utility-scale solar development in the solar energy zones (SEZ) of six southwestern states based upon the renewable portfolio standards (RPS) during 2015–2030. Results showed that solar PV was the most appropriate technology for water-limited regions. Sufficient land was available within the 19 SEZs to meet the RPS requirements. Available water was adequate to meet RPS solar carve-out water requirements for Nevada and New Mexico. For future work, the generated model can be modified to analyze the performances of renewables in addition to solar.

1. Introduction

Solar technology is emerging as a popular form of alternative energy, but reliance on traditional technology based on fossil fuels for energy production is still quite large. In 2015, 67% of the electricity production in the U.S. was achieved by using fossil fuels and 13% by using renewable energy sources; only 0.65% of the electricity production was achieved by using solar energy [1].

Fossil fuels have environmental as well as economic costs. Usage of traditional fossil-fuel sources have led to an increased carbon footprint, among other environmental disruptions. The links among greenhouse gas (GHG) emissions, the consequent pollution, and the changing climate may potentially lead to an increase in climate extremes around the globe [2]. Various studies connect the changing climate to intensified droughts and elevated temperatures [3,4], wildfires, a rise in sea levels, floods, and storms. Coupled with a growing population, the changing climate brings about socioeconomic issues regarding water availability [2]. Additionally, finite and depleting levels and oscillating prices of fossil fuels [5,6], rising pollution levels, and political compromises [7] are among the factors that have resulted in an increase in the attractiveness of energy efficiency and clean-energy technology. In particular, this increase can be attributed to the fact that clean-energy technology represents reduced GHG emissions and other reduced waste products during the various life cycle processes [8–13].

Many countries are turning towards clean energy technologies, setting target goals and incorporating them into the national energy policies to aid in clean energy technology development [5,14–17]. Among renewable energy resources, solar energy is growing at a rapid pace due to technological advancements that have led to increased efficiency and decreased costs. Solar energy provides several benefits, including reductions in the carbon footprint, increased job opportunities, provision of energy independence at remote locations, and an enhanced quality of life [9].

This study, composed of two parts, analyzed the potential of using solar technology in the southwest U.S. The first part of the study generated harmonized water and land use estimates related to solar energy.

Abbreviations: AW, Appropriated Surface Water/Groundwater; BGW, Brackish Groundwater; DR, Distributed Renewables; LBL, Lawrence Berkeley Laboratory; RPG, Renewable Portfolio Goals; RPS, Renewable Portfolio Standards; SAW-1, Scenario 1 for available water; SAW-2, Scenario 2 for available water; SAW-3, Scenario 3 for available water; SEZ, Solar Energy Zone; SD, System Dynamics; UGW, Unappropriated Groundwater; USW, Unappropriated Surface Water; WW, Municipal Waste Water

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The second part involved comparing water and land demands for various solar technologies against water and land availabilities from 2015 to 2030, as well as quantifying the associated reduction in carbon emissions. This study used a simulation model for the analysis.

Typically, solar technology can be categorized as either photovoltaic (PV) or concentrated solar power (CSP). The efficiency of the PV panels is greatly dependent upon the material it is made of, which can be categorized as silicon-based (e.g., crystalline silicone (C-Si) or thin-film silicon (thin-film Si)) or non-silicone-based (e.g., concentrated photovoltaics (CPV), or thin-film cadmium telluride (CdTe)). PV systems using C-Si are more efficient, but also costlier, than those using thin-film Si material. Typically, PV technologies employing C-Si and CdTe materials are deployed on large scales, whereas those utilizing thin-film Si are deployed on smaller scales [18].

CSP technology may broadly be classified as a dish stirling, a linear Fresnel, a parabolic trough, and a power tower. The most popular CSP technologies are power tower and parabolic trough, since power tower has the highest efficiency among CSP technologies [19]; likewise, parabolic troughs are preferable over linear fresnels. The cheaper cost of flat mirrors lowers the capital cost of linear fresnels, but they are also the least efficient compared to other CSP technologies. Similar to solar PV, dish Stirling generates electricity directly, but the addition of a complicated Stirling engine makes the simpler PV systems preferable over dish stirling systems.

Electricity generation requires water usage. In 2010, approximately 45% of the water withdrawals in the U.S. were for thermoelectric power plants [20]. For solar facilities, the on-site water requirements are related to plant construction, operations, and dismantling of the plant. Water use for plant construction is typically required for dust suppression during site grading. Dismantling water use is required during disassembling a solar facility. Estimates for the life-cycle water usage of various electricity generation technologies, including solar systems, were generated by [21] based on the literature review of over 2000 publications. Harmonized values of water use for solar facilities were generated by [21] for upstream and downstream (aggregate water use estimate encompassing manufacture of panels/mirrors, and construction, dismantling, and disposal of solar facilities) processes, in units of gallons MWh^{-1} of electricity generation; median estimates were also generated for operational water use.

Solar facilities have operational water requirements (panel/mirror washing and cooling). Median estimates for operational water consumption and withdrawal were generated by [21] and [22] for various electricity generating technologies, including solar systems. Existing literature reports solar water requirements using different assumptions. Harmonization performance may help remove inconsistencies and data assumptions across various studies.

Water is required for both CSP and PV technologies to clean the mirrors and panels in order to prevent a reduction in the efficiency of the system. The water requirement for washing ranges from 0.08 m^3 MWh^{-1} to 0.15 m^3 MWh^{-1} [23]. The frequency of cleaning depends on characteristics of the site (soil and dust properties, vegetation, air pollution, wind speed and direction, humidity, temperature as well as the intensity, frequency, and duration of precipitation) and the solar system (panel/mirrors orientation and angle of tilt, glazing properties) [24,25].

In arid desert-like regions, dust is predominantly inorganic and windborne and adheres to the solar panel/mirror's glass exterior due to electrostatic forces of attraction and dry winds. Weekly cleanings are required in such dry climatic conditions. [26] conducted field-testing for determination of the threshold velocity that will cause dust generation for various desert soils of the Mohave Desert, including playas (over 100 cm s^{-1} for disturbed soils and over 150 cm s^{-1} for undisturbed soils) and alluvial fans (40–70 cm s^{-1} for disturbed soils and above 200 cm s^{-1} for undisturbed soils). Soiling of panels/mirrors is found to be greatest in North Africa and Middle Eastern regions [27,28]. [29] conducted a literature review of various studies regarding impact of dust accumulation of solar facilities between the years 2012–2015. The study reported that a 1.5-year soiling study for PV(C-Si) in Mesa, AZ showed a 74.6gm m^{-2} accumulation of dust, resulting in very high efficiency losses. [29] further reports that another 3-month cold weather study in Mesa, AZ resulted in 2% and 1% efficiency losses for tilt angles of 0° and 33°, respectively. [28] determined degradation rates for PV module efficiencies due to dust accumulation for one day (6.2%), seven days (11.8%) and thirty days (18.7%). [30] reviewed performance characteristics of PV modules exposed to dust and found that dust accumulation decreases both current and voltage output, unlike smog or air pollutions that only cause a decrease in current output.

CSP technology has additional water requirements for cooling processes. Cooling methods can be categorized as wet, dry, and hybrid [23]. Water usage of CSP plants is similar to that of traditional thermoelectric power technologies. The wet cooling process has the highest efficiency among all cooling methods, is the least inexpensive, and is the most popular. However, wet cooling encompasses the highest water usage, in the range of 3.1–3.8 m^3 MWh^{-1} [21,31,32]. Water usage of a hybrid-cooled system, in the range of 0.6–1.3 m^3 MWh^{-1}, is approximately 65-80% lower than that of a wet-cooled system [21,31,32]. Among the three, dry cooling is relatively costly and a less efficient method but encompasses the lowest water usage in the range of 0.1–0.4 m^3 MWh^{-1} [21,31,32].

The southwestern U.S. is abundant in solar resources and favorable for solar deployment [33], but development of solar power in the region might be curtailed due to the limited availability of water. The southwest is the driest region in United States [34]. Low annual average precipitation, climate fluctuations, increasing population, and changing water needs have placed an increased demand on existing water resources [35,36]. Drought conditions prevalent in the region augment this problem [37]. Since utility-scale solar is typically deployed at remote locations, the scarcity of water in the southwest may be a hindrance to solar power development.

Any new development necessitates new water use, which could be made available from five sources of water [38–40]: (1) Unappropriated surface water (USW), (2) Unappropriated groundwater (UGW), (3) Appropriated surface water/ groundwater (AW), (4) Municipal wastewater (WW), and (5) Brackish groundwater (BGW). Rights to USW and UGW are obtained directly from the state through the state's water management department. For utility-scale solar projects, which are typically positioned at remote locations, groundwater resources have become the only feasible and cost-effective option.

In case of the unavailability of freshwater resources, utilizing WW or BGW becomes an option but will require treatment. For WW, in addition to treatment, costs will include leasing municipal WW and transporting it to the solar facility. For utilizing BGW, which contains total dissolved solids in the range of 1500–10,000 mg l^{-1}, in addition to well drilling, costs are incurred for freshwater generation using reverse osmosis process [41]. Desalination becomes feasible when the cost of hauling freshwater over long distances is higher than the cost of desalination or if low-cost energy resources are available, since desalination is an energy intensive process [42]. Deeper understanding of the nexus between solar energy and water is essential for successful application of solar policies in the region.

Utility-scale solar development requires a huge land area. The land requirement of a PV solar plant is contingent upon the tracking type of the PV panel, i.e., a flat-paneled, fixed-tilt, or tracking mechanism. The panels may be mounted onto a fixed axis facing south or on a tracking mechanism that tracks the sun for capturing of the maximum solar irradiance. The tilt angle of fixed-tilt panels corresponds to the local latitude in order to capture more energy throughout the year [43]. Land usage increases as tilt angles increase [44]. However, to generate the same amount of energy as that of a tracking type PV, fixed-tilt PVs have additional panel/ system requirements, making them comparatively more expensive than other types.

Compared to fixed-tilt panels, tracking systems have larger land requirements, but the energy generation is also higher. A single-axis