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

Saria Bukhary, Sajjad Ahmad*, Jacimaria Batista

Department of Civil and Environmental Engineering and Construction, University of Nevada, Las Vegas, 4505 S. Maryland Parkway, Las Vegas, NV 89154-4015, USA

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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

* Corresponding author.
E-mail address: sajjad.ahmad@unlv.edu (S. Ahmad).

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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

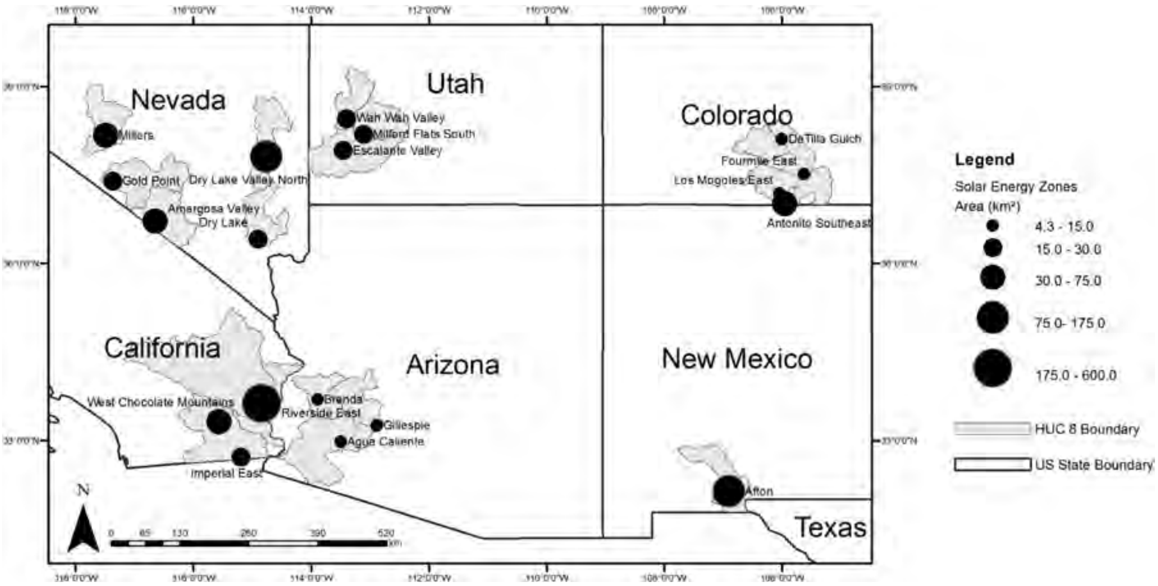

Fig. 1. Map of the six states of the southwestern U.S., showing the 19 solar-energy zones and the corresponding 8-digit HUC regions.

tracking system orients the PV panel towards the sun by rotating it about its vertical axis. A double-axis tracking mechanism also will rotate the panel about its horizontal axis, but uses more land than its relative increase in energy production merits. Apart from the area required for mirrors/panels, there are additional land requirements for maintenance activities, access, and avoiding self-shading [44,45].

Tracking mechanisms are also used for CSP systems. Provisions for energy storage at a CSP facility may increase the production of energy in terms of land usage [45]. Since solar deployment requires a large amount of land, land might be utilized that otherwise would be used for food production. [44] concluded that the electric footprint for solar PVs involved less than 2% of the land utilized for cultivating crops and grazing activities in the United States. [13] found that for operational life greater than 25 years, a solar power plant utilized a lower amount of land kWh^{-1} compared to a coal-power plant.

Solar technology represents zero carbon emissions during a plant's operation; however, certain carbon emissions are connected with the manufacture of panels and mirrors as well as during construction and transportation [9]. Desert environment, which is characterized by an abundance of year-round solar irradiance, solar deployment presents a viable option. In contrast, removing vegetation in forested areas in order to install a utility-scale solar power plant has the potential of increasing the life-cycle carbon dioxide (CO_2) emissions of the plant, ranging from 16 to 86 g CO_2 kWh^{-1} [13]. Therefore, using desert lands for utility-scale solar plants offer additional gains. One-third of the earth's land surface is covered with deserts [39,40] [46,47]. If 4% of the deserts are utilized for solar energy production, the generated power will be able to meet the world's energy demands [48]. For solar technologies, [49] reported carbon emissions for CSP trough and CSP tower as 26 and 38 g CO_{2eq} kWh^{-1}, respectively. [50] provided emissions for PV (C-Si) as 45 g CO_{2eq} kWh^{-1}. [51] estimated emissions for PV thin-film amorphous silicon and PV thin-film cadmium telluride as 21 and 14 g CO_{2eq} kWh^{-1}, respectively.

Simulation modeling may play an instrumental role in the progress of solar power. System dynamics (SD) is an approach developed by Forrester [52–56] that is used by researchers to analyze the dynamic behavior of systems in various fields, including planning for traditional and renewable energy [57–65], analyzing social behavior [66], evaluating such environmental changes as GHG emissions [50,67–69], cost analysis [5,50,70], and policy-based environmental management, like water resources management [71–75], and energy management [76–78]. [5] developed a SD model to compare the costs of developing different kinds of clean-energy technologies in the U.S for electricity generation from 2010 to 2030. [60] performed a simulation for a period from 2010 to 2050 by using an SD model to determine the availability of the material tellurium for use in cadmium telluride PVs. The study determined that SD models generate better results than other models that use static assumptions [60].

The objectives of the current study are two-fold:

- The first objective was to generate harmonized water (construction, operation and dismantling) and land use (direct and total) estimates using the parameters relevant to the southwestern US.
- The second objective was to make quantitative assessments of water usage and its availability, land usage and availability, and associated reduction in carbon emissions for utility-scale solar deployment based on the renewable portfolio standards (RPS) of six southwestern states from 2015 to 2030 by generating a simulation model.

This simulation model may be used as a screening tool for potential investments, in decision making for solar project applications, for permit approvals, and for future energy planning.

2. Study area

To promote solar technology, the U.S. Bureau of Land Management (BLM) initiated the Western Solar Plan in 2012 [79]. A solar energy zone (SEZ), as defined by BLM, is a priority area of land to be used for utility-scale solar installations based on its suitability. Renewable portfolio standards or renewable energy standards are standards and policies adopted by various states in the U.S., and they require that some portion of the state's electricity be generated using such renewable means as wind, solar, hydropower, geothermal, and biomass. The policies target utility-scale power production as well as distributed generation. Utility-scale projects are grid-connected and have capacities greater than 20 MW.

With the purpose of furthering development of utility-scale solar technology, 19 SEZs, located in Arizona (AZ), California (CA), Colorado (CO), Nevada (NV), New Mexico (NM), and Utah (UT) and totaling over 1207 km^2 in area, were recognized by the Western Solar Plan (Fig. 1). Although utility–scale solar projects can be established outside of these zones by means of a process, these SEZs are located in areas that offer minimum environmental disruption due to solar deployment. In

Table 1
Details about the 19 Solar-Energy Zones in AZ, CA, CO, NM, NV, and UT.

S.N.	SEZ	SEZ area (km^2)	State	SEZ county/2015 population	HUC-8 region	SEZ location	Annual precipitation (mm)	Water availability (Million m^3/year)			
								UGW	AW	BGW	WW
1.	Agua Caliente	10.32	AZ	Yuma/204,275	15070201	Lies in the Palomas Plain, surrounded by the Palomas and Baragan Mountain. The Gila River runs 8 km to the south. Sparsely populated surrounding area.	102	0.00	22.04	139.25	0.60
2.	Brenda	13.5		La Paz/20,152	15030105	Lies within the Ranegras Plain, surrounded by the Bouse and Bear Hills, Plomosa, Granite Wash and Harquahala Mountains.	100–200	0.00	6.39	50.57	0.00
3.	Gillespie	11		Maricopa/4.167,947	15070104	Surrounded by the Gila Bend Mountains and Centennial Wash.	< 200	0.00	6.61	29.51	0.00
4.	Imperial East	23.1	CA	Imperial/180,191	18100204	Located in the Sonoran Desert and within the jurisdiction of the California Desert Conservation Area (CDCA) in East Mesa. The All-American Canal runs along the south of SEZ.	80–100	0.00	1.97	12.70	0.00
5.	Riverside East	598.6		Riverside/2,361,026	18100100 15030104	Located within the Mojave Desert, in Chuckwalla Valley, the South Palen Valley, and CDCA. Consists of flat barren plains with sandy portions. Areas surrounding the SEZ are developed.	100–150	0.00	23.60	14.08	2.58
6.	West Chocolate Mountains	43.5		Imperial/180,191	18100204	Located in Colorado Desert, surrounded by the Salton Sea and Chocolate Mountains Aerial Gunnery Range. Gently sloping topography towards the Salton Sea.	51–203	0.00	1.97	12.70	0.00
7.	Antonito Southeast	39.3	CO	Conejos/8130	13010002	Lies in the San Luis Valley, surrounded by the San Juan Mountains and Sangre de Cristo Range. The terrain is flat to gently rolling.	200	0.00	7.36	0.00	0.00
8.	De Tilla Gulch	4.3		Saguache/6251	13010004	Located in the northwest part of San Luis Valley, in the San Luis Basin. SEZ terrain is gently sloping. Some development exists in surrounding areas.	200	0.00	3.62	0.00	0.00
9.	Fournile East	11.7		Alamosa/16,496	13010003	Lies in the eastern San Luis Valley, on a flat alluvial fan in the high-elevation San Luis Basin.	200	0.00	4.04	1.38	0.00
10.	Los Mogotes East	10.8		Conejos/8130	13010002	Located in the southwestern San Luis Valley, on a flat alluvial fan in San Luis Basin.	200	0.00	7.36	0.00	0.00
11.	Afton	121.2	NM	Dona Ana/214,295	13030102	Lies in the West Mesa of Mesilla Basin, bounded by Mesilla Valley, Robledo, and West Potrillo Mountains and the Hills of Rough and Ready, Aden, and Sleeping Lady.	170–240	0.00	2.78	34.54	7.37
12.	Amargosa Valley	34.3	NV	Nye/42,477	18090202	Lies in the Amargosa Desert, which is bounded by the Funeral Mountains and Yucca Mountain.	100	0.02	0.27	0.00	0.00
13.	Dry Lake	23		Clark/2114,801	15010012	Lies in Dry Lake Valley, surrounded by the Arrow Canyon Range to the west and Dry Lake Range to the southeast.	130	28.34	0.21	1.38	0.00
14.	Dry Lake Valley North	101.5		Lincoln/5036	16060009	Lies within Dry Lake Valley, and is bounded on the west by the North Pahroc Range and on the east by the ranges of Black Canyon, Bristol, Burnt Springs, Ely Springs, Highland, and West Range.	180–410	0.42	0.51	0.00	0.00
15.	Gold Point	18.6		Esmeralda/829	16060013	Lies within Lida Valley, surrounded by Palmetto and Stonewell Mountains.	80–150	5.13	0.26	0.00	0.00
16.	Millers	66.9			16060003	Situated in Big Smoky Valley, surrounded by Monte Cristo Range, Lone, and San Antonio Mountains.	130	3.32	0.16	0.00	0.76
17.	Escalante Valley	26.4	UT	Iron/48,368	16030006	Situated in the southern part of Escalante Desert, framed by Antelope Range, Shauntie Hills Mineral, Black, and Wah Wah Mountains.	200	0.00	3.32	2.94	0.31
18.	Milford Flats South	25.3		Beaver/6354	16030007	Situated in the northeastern part of Escalante Desert, surrounded by Shauntie Hills, Mineral, Black and Wah Wah Mountains.	200	0.00	1.36	0.00	1.66
19.	Wah Wah Valley	23.8		Beaver/6354	16030009	Situated in Wah Wah Valley, bounded by Shauntie Hills, Wah Wah and San Francisco Mountains	180	3.59	2.69	1.38	0.00

addition, they have access to various services such as major roads and electricity transmission lines, are exposed to some of the highest levels of solar irradiance in the world, and offer incentives under the Western Solar Plan [23,79,80] (Table 1).

Some non-development areas have also been identified within the SEZ due to the occurrence of wetlands, lakes, streams, canals and major washes. The area coverage of each SEZ shown in km^2 in Table 1 is reflective of development areas only [80]. Utility-scale solar necessitates relatively flat land for cost effective deployment; locations with gentle slopes of less than 5% were selected as SEZs [79]. In addition, SEZs are located where direct normal irradiation (DNI) levels are at least 6.5 kWh m^{-2} day^{-1} or greater.

As shown by Fig. 1, three SEZs are located in AZ, CA and UT, four are located in CO, five are in NV, and one is located in NM. Basic details about the 19 SEZs are listed in Table 1, which reviews and summarizes information provided by [79] and the Final Solar Energy Development Programmatic Environmental Impact Statement [80]. County populations were obtained from [81]. The aforementioned SEZs are located in arid to semi-arid undeveloped scrublands. Areas surrounding the SEZs predominantly are undeveloped and rural with a few exceptions (Table 1). The most common vegetation among the SEZs is the creosote bush, low shrubs, and some low trees.

The SEZs typically have dry soil conditions as well as normal occurrences of high winds [80]. Dust samples of the southwest U.S. show the largest particle diameters to be between 0.02 and 0.1 mm [26]. Some of the SEZs are areas of dry lake beds or playas (Table 1). Such areas contain fine-grained soils infused with salts, and hence may produce saline/alkaline dust [82]. Other SEZs are alluvial flats that are also contributors of dust (Table 1). This dust is carried by wind and may accumulate on the surface of solar panels/mirrors, requiring washing to maintain system efficiency.

3. Data

3.1. Renewable portfolio standards

The RPS of the six states (AZ, CA, CO, NM, NV, and UT) are shown in Table 2 and are based on information provided by the Database of State Incentives for Renewables & Efficiency [83]. Under the RPS, adoption of renewables would lead to the provision of federal incentives and tax rebates [83]. The states may have incorporated specific standards and goals related to solar deployment or distributed renewables (DR) as a part of RPS. However, in the southwest U.S., only NV and NM have solar carve-outs or RPS targets related to solar power development (Table 2). AZ, CO, and NM have incorporated DR targets within the RPS requirements; distributed solar deployment is not the scope of this work. In the current study, it was assumed that RPS-based solar power development was solely utility-scale. In this study, the data was incorporated within the simulation model to reflect the states' energy policies. Since the implementation of the targets is contingent upon cost effectiveness of the renewable projects, Utah is considered to have renewable portfolio goals (RPG), not renewable portfolio standards.

Table 2
Renewable portfolio standards and goals for AZ, CA, CO, NM, NV, and UT.

State	RPS and RPG: contribution % of renewables for electricity production/ target year	Solar carve-out
AZ	15% by 2025	–
CA	50% by 2030	–
CO	30% by 2020 (investor owned utilities); 20% by 2020 (electric cooperatives); 10% by 2020 (municipal utilities)	–
NM	20% by 2020 (Investor owned utilities) 10% by 2020 (Rural electric cooperatives)	20% of RPS from solar i.e., 4% of total retail sales
NV	25% by 2025	5% of RPS by 2015 and 6% from 2016 to 2025 i.e., 1.5% of total retail sales
UT	20% by 2025	–

3.2. Water availability

Estimates for water availability (AW, BGW, UGW, and WW) for the 19 solar-energy zones in the six states of southwestern U.S. were obtained from [40] (Table 1, Fig. 2). The data in that study were collected from the states in collaboration with each state's experts in water data. In addition, the water plans for these states were utilized. Gaps in the data were filled by using the data from such sources as the U.S. Geological Survey, the U.S. Environmental Protection Agency, and the U.S. Energy Information Administration [40]. The water data were translated into eight-digit Hydrologic Unit Codes (HUCs) via the method of aggregation/averaging. Furthermore, [40] projected water availability from 2010 to 2030. This data was included in the simulation model in the current study to compare water availability estimates with water-demand projections for solar deployment in the 19 SEZs.

3.3. Water usage

Within the framework of the simulation model in this study, water consumption and withdrawal for PV and CSP systems was estimated based on the work of [21] as well as the review of approximately 50 related publications between the periods of 2013–2017, of which two were selected. The water use estimates generated by the current study were related to plant construction, operations and dismantling.

3.4. Land availability

Data regarding the land area available within the SEZs were extracted from [79,80] (Table 1).

3.5. Land usage

Land usage was computed for utility-scale solar plants based on the work of [84]. This study computed land usage associated with utility-scale solar power generation by using three different methods, based on the form of available data. Dataset used in the insolation method computations by [84] was also used by the current study because of the adaptability of the data for the performance of harmonization accomplished in the current study. Review of approximately 50 publications between 2013 and 2017 were also made, but none of them were selected because of the absence of relevant parameters.

3.6. States' electricity projections

Projection estimates for RPS-based electricity consumption, in units of GWh, were acquired from Lawrence Berkeley Laboratory (LBL) for the states of AZ, CA, CO, NM and NV. In order to generate electricity projections, the dataset was developed by [85] by multiplying region-based growth rates acquired from the U.S. Energy Information Agency with the state estimates for retail electricity sales. RPS-based electricity projections were estimated by multiplying RPS target percentages with retail electricity projections. Utah's electricity projection was acquired by means of personal communication with Galen Barbose, who is associated with LBL.

Transmission and distribution losses, also known as line losses, were taken as 6% of retail electricity sales [86] in order to determine electricity generation at utility-scale solar installations [87].

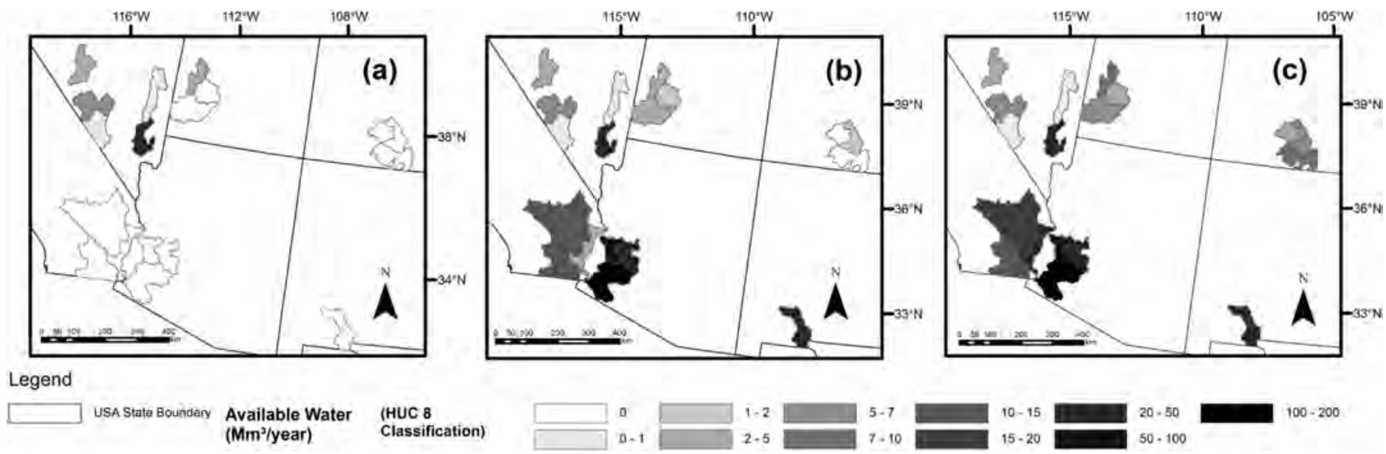

Fig. 2. Water availability for the 19 solar-energy zones in six southwestern states for three scenarios. (a) Scenario 1: Unappropriated available water is the summation of unappropriated groundwater and unappropriated surface water resources (SAW-1); (b) Scenario 2: Available water is the summation of brackish groundwater, unappropriated groundwater, unappropriated surface water, and wastewater (SAW-2); (c) Scenario 3: Available water is the summation of appropriated water, brackish groundwater, unappropriated groundwater, unappropriated surface water, and wastewater (SAW-3). Water availability estimates were extracted from [40].

3.7. Carbon emissions

Estimations of carbon emissions were made using median values for carbon emissions obtained from [88] (Table 3) and the 2014 energy-source distribution of electricity generation [89] for the six southwestern states (Table 4). Energy-source distribution was assumed to stay constant between 2015 and 2030, due to lack of data.

4. Methodology

The aim of the current work was to make quantitative assessments of water and land-use of solar facilities, land and water demands of solar technologies to be deployed in the SEZs, and of how well they compare against the water and land availabilities of these zones. What portion of the states' RPS can be met in these zones, and what is the associated reduction in carbon emissions?

4.1. Solar water and land usage

In the current study, water and land–use estimates for solar technologies were generated by review of over 150 publications and harmonization of published estimates.

Studies for estimating on-site water use of solar facilities are limited. In the current study, the harmonized water withdrawal and consumption estimates generated are reflective of onsite water use of solar facilities related to plant construction, operation, and dismantling. Harmonization was performed by using parameters relevant to the southwestern United States. Dataset provided by [21], which was comprised of 20 publications for upstream and downstream water use values, was reviewed, among which 6 publications were selected; 8 out of 26 publications related to operational water use values were selected. In addition to the dataset provided by [21], 2 of approximately 50 studies published between the years 2013–2017 were reviewed and included in the pool of studies. Thirty five water estimates (n) were provided in the selected publications for generation of harmonized water use related to construction and dismantling, whereas 29 estimates were used to generate harmonized water use for operation of PV and CSP systems. Only those data sets that quantified water use estimates and provided relevant parameters that were required for harmonization were retained.

Harmonized and use estimates were generated for various configurations of utility-scale solar plants based on the dataset provided by [84], as discussed in Section 3.5. [84] estimates land use of solar technologies by using the following equation:

$$L = \frac{P}{(I)(SE)}$$

where L = Land-Use estimate ($m^2\,MWh^{-1}\,yr$), P = Packing factor (unitless), I = solar insolation ($MWh\,m^{-2}\,yr^{-1}$), and SE = Solar-to-electric efficiency (unitless)

Packing factor is the ratio of the total land area covered by the array, including area provided to avoid shading and maintenance activities, to the actual area covered by panels/mirrors. *Direct land*, or *L,* is the area occupied by solar infrastructure. In comparison, *Total land* is the fenced zone of a utility-scale solar plant. Total land area is approximately 1.4 times the direct land area for both PV and CSP systems [45].

Table 3
Carbon emissions for various energy sources.

Energy sources for electricity generation	Carbon emissions ($gCO_{2eq}\,kWh^{-1}$)
Coal	1001
Natural Gas	469
Petroleum	840
Nuclear	16
Hydropower	4
Bio-power	18
Geothermal	45
Wind	12
Solar PV	46
Solar CSP	22

Table 4
2014 percentages for electricity power consumption by sector for the six southwestern states based on source distributions, which were utilized for the estimation of carbon emissions.

Source	Electric power sector consumption percentage					
	AZ	CA	CO	NM	NV	UT
Coal	40.66	0.43	63.93	66.45	23.51	80.59
Natural Gas	19.43	53.30	19.05	24.70	56.41	14.77
Petroleum	0.06	0.04	0.04	0.22	0.07	0.05
Nuclear	31.04	11.03	0.00	0.00	0.00	0.00
Hydroelectric	5.34	9.75	3.14	0.28	7.42	1.46
Biomass	0.33	4.85	0.34	0.09	0.10	0.37
Geothermal	0.00	7.14	0.00	0.03	8.50	1.22
Solar/PV	2.73	5.80	0.43	1.52	3.04	0.00
Wind	0.41	7.66	13.08	6.71	0.95	1.54

4.2. Harmonization procedure

Harmonization is performed to remove inconsistencies and data assumptions across various studies, and to generate a single "best" estimate. To perform harmonization, the following equations were used [21,50,90]:

$$Ni,\ harm = \frac{(N_{i,pub})(I_{pub})(ME_{pub})((PR_{pub}))(LT_{pub})}{(I_{harm})(ME_{harm})(PR_{harm})(LT_{harm})}$$

$$Ni,\ harm = \frac{(N_{i,pub})(I_{pub})(SE_{pub})(LT_{pub})}{(I_{harm})(SE_{harm})(LT_{harm})}$$

where, *Harm* = Harmonized, *Pub* = Published, *N* = Water or Land use estimate, *I* = solar insolation, *ME* = Module Efficiency, *PR* = Performance Ratio, *LT* = Lifetime, *SE* = Solar-to-electric efficiency, *PV* = Photovoltaic, and *CSP* = Concentrated Solar Power

For harmonization, a solar-to-electric efficiency of 20% was used for CSP-Tower and 16% for CSP-Trough [91]. For harmonization, module efficiency of 19.3% was used, as the mean of the module efficiencies reported by [18], for mature PV technologies deployed at large-scale.

Performance ratio assesses the system performance of solar PV. PV System efficiency is a product of performance ratio and module efficiency. A performance ratio of 0.8 was used based on the review of previous studies [21,50,92].

Typically, design lifetime of solar technologies is 30 years [21,50]. This estimate was used for performance of harmonization for both PV and CSP systems. Solar insolation of 2400 kWh m^{-2} yr^{-1} was used, which is reflective of the limiting direct normal insolation value for SEZs. This is also a typical value used for performance of harmonization for the southwestern United States [50,51].

For this study, median estimates were chosen to represent data variability across multiple studies, as is the case in various other harmonization studies. Median is a resilient measure since it is not affected by outliers. These generated estimates for water and land-use intensities were incorporated in the simulation model to generate RPS-based water and land demands for the 19 SEZs. Finally, the estimates generated are not intended to characterize all potential types of a certain solar technology.

4.3. Simulation Modeling

Modeling softwares may play an instrumental role in the progress of solar power. System Advisor Model (SAM) was developed by the U.S. Department of Energy and the National Renewable Energy Laboratory (NREL) [93] to analyze system performance and energy costs for grid-connected renewable-energy power projects. The Solar Deployment System (SolarDS) model, developed by NREL [94], simulates the financial performance of PV technology on building rooftops in United States through 2030.

Stella, a popular SD modeling tool, was employed in this study to generate a dynamic system model [95]. The software helps to analyze different scenarios by running them repeatedly until favorable results are accomplished. System Dynamics tools also may characterize unknown features of a system by generating unforeseen results. A user interface assists in enabling a model that is easy to understand and can assist in generating the results as well. In this study, modeling consisted of the following major steps: (a) Understanding and defining the problem, (b) Building the model based on the problem, (c) Parameterizing the model, (d) Calibrating and validating the model, (e) Analyzing the policies based on the model results, and (f) Recommending policy improvements.

The relationship between solar installations and carbon emissions, as well as water and land requirements and availability, were determined and generated as a simulation model for the 19 SEZs. Analysis was conducted for the period of 2015 through 2030.

4.4. Water and land availability and demand

Projections for RPS-based water and land demands were generated by the simulation model for utility-scale solar plants, in the SEZs of the six states for 2015–2030, by taking the product of RPS-based electricity generation projections at utility-scale solar installations and the harmonized water and land-use intensities. RPS-based water and land demand projections for SEZs were then compared against the available water and land of the SEZs, respectively, to determine the contribution of SEZs in fulfilling the RPS of the states. Both PV and CSP technologies were analyzed and comparisons were drawn. This exercise proved useful in determining which solar technologies were favorable to be deployed in the SEZs based on the available water and land resources. Projected water demands were compared against available water for the following three scenarios (Fig. 2):

- Scenario 1 for available water (SAW-1) is the sum of estimates for UGW and USW.
- Scenario 2 for available water (SAW-2) is the sum of the estimates of BGW, UGW, USW, and WW.
- Scenario 3 for available water (SAW-3) is the sum of the estimates of AW, BGW, UGW, USW, and WW for SEZs.

Since USW was not available in SEZs, SAW-1 only reflected estimates for UGW. Making use of WW or BGW resources as depicted by SAW-2 may become the only feasible alternative for water-limited areas, but this resource warrants additional costs. Since AW estimates were based largely on the assumption that 5% of the water rights associated with irrigation of low-value crops would be transferred or abandoned [40], SAW-2 may represent a more realistic representation of the total water resources available within the SEZs than SAW-3.

Next, the overall contribution of SEZs for each of the six southwestern states was determined by taking the aggregate of the individual RPS-based contribution of the SEZs located in each state. Based on whether the SEZs were water-limited with respect to the scenarios of SAW-1, SAW-2, and SAW-3 or land limited, contribution was depicted as three scenarios: SC-1, SC-2 and SC-3, respectively.

In the current study, it was assumed that RPS based solar power development was solely utility-scale, and DR carve-outs were not incorporated within the simulation model. The simulation model made computations such that, for various configurations of PV and CSP systems, each solar technology fulfilled 100% of the scenario requirements for every model run. Scenarios for solar-based electricity generation for each southwestern state were simulated as a percentage of the RPS/RPG in order to determine the optimum match between demand and availability for water and land use.

Finally, the simulation model generated in the current study is based on certain assumptions and may be employed as a screening tool or for a crude assessment of future energy planning, solar project applications, permit approvals, but it should not be used as a final decisive tool.

4.5. Carbon emissions

Carbon emissions generated by the implementation of solar installations in the 19 SEZs of the southwest were generated by using median life cycle carbon emissions (Table 3) and the energy-source distribution of electricity generation for six southwestern states (Table 4). Net reductions in carbon emissions were estimated via the simulation model by assuming that the PV or CSP technology fulfilled 100% of the scenario requirements for every model run and comparing it to whether or not the current distribution of various energy sources fulfilled 100% of the scenario requirements for each model run. During the operational life of solar facilities, carbon emissions are negligible. Carbon emissions are only associated with the manufacturing phase of mirrors and panels.

Table 5
Summary statistics of harmonized water withdrawal and consumption estimates for photovoltaics (PV) and concentrated solar power (CSP) during plant construction, operation and dismantling.

	Solar technology	Water withdrawal (gal MWh^{-1})				Water consumption (gal MWh^{-1})			
		Median	Min	Max	n	Median	Min	Max	n
Plant construction	CSP-Tower	46	46	46	1	4	3	63	9
	CSP-Trough	58	58	58	1	10	9	56	3
	PV	4.7	4.7	4.7	1	4.7	4.7	4.7	1
Plant operations	CSP-Tower Wet Cooling	520	400	640	2	520	400	640	2
	CSP-Tower Dry Cooling	130	110	160	8	130	110	160	8
	CSP-Trough Wet Cooling	930	580	1320	5	930	580	1320	5
	CSP-Trough Dry Cooling	71	68	165	8	71	68	165	8
	PV	8.6	4	13	2	8.6	4	13	2
	CPV	14	11	36	4	14	11	36	4
Plant dismantling	CSP-Tower	0.24	0.24	0.24	8	0.24	0.24	0.24	8
	CSP-Trough	0.16	0.15	0.16	2	0.16	0.15	0.16	2
	PV	0.26	0.19	2.4	20	0.26	0.19	2.4	20

5. Results and discussion

This section explains harmonized estimates of water and land use values that were later incorporated into the simulation model. Model validation and sensitivity analysis of the harmonized estimates are also discussed. This section also details the simulation model results for water and land availability and usage and associated reduction in CO_2 emissions for the development of utility-scale solar power in the six southwestern states of AZ, CA, CO, NM, NV and UT.

5.1. Harmonization

Summary statistics for harmonization performed for land-use intensity estimates, as well as water withdrawal and consumption estimates, for solar facilities are summarized in Tables 5 and 6. Median value was chosen to represent the central tendency of the collected data. The minimum and the maximum of the water and land use intensity estimates retained for the performance of harmonization may not encompass the entirety of minimums and maximums associated with various on-site scenarios and technological variants. The results have been reported in two significant digits to represent the uncertainty and variability of the retained data (Tables 5 and 6).

Water withdrawal estimates were reported by very few of the selected publications. Other than constructions estimates, water withdrawal was assumed to be equal to water consumption estimates. This is a reasonable assumption since, at the solar facility, water required for mirror and panel washing is not recollected; it is either evaporated or infiltrated in the ground. For CSP systems, evaporation ponds are typically used to dispose process water.

Water required during the construction phase is mostly used for dust suppression during site grading [96,97]. Water use during the construction phase can be reduced by employing techniques that reduce earth movement for site preparation [96]. The 19 SEZs have been sited at locations with gentle slopes of less than 5%; considerable site grading may not be required. Water consumption associated with the construction of CSP-tower was found to be 9% of the water withdrawal for CSP-tower construction. Water consumption associated with the construction of CSP-trough was found to be 17% of the water withdrawal for CSP-trough construction. If reclaimed water or process water is to be used for dust suppression, permitting is required.

For solar facilities, operational water requirements were found to be dominant compared to the water requirements for construction and dismantling. During operation, water is required for mirror and panel washing for PV and CSP systems. CSP systems have additional water requirements for cooling purposes. Water use shown in Table 5 for CSP systems combines water required for mirror washing and cooling. CSP-tower dry cooling utilized 75% less operational water compared to CSP-tower wet cooling technology. CSP-trough dry cooling utilized 90% less operational water compared to CSP-tower wet cooling technology.

Monocrystalline silicone, multicrystalline silicone, and cadmium telluride are mature photovoltaic materials that are typically used for utility-scale solar plants [18], hence, the PV literature selected consisted of these PV materials. PV systems were shown to be the smallest consumers of water among solar systems. Since the construction and dismantling water estimates for CPV systems were not found in the literature, those were assumed to be equal to PV systems as shown in Table 5.

Overall, water requirements were found to be smallest for PV technology and largest for CSP-trough during construction and operation. PV systems were found to be the largest consumers of water during the dismantling phase. Dismantling water estimates are those required during disassembling a solar power plant, and they were found to be

Table 6
Summary statistics of harmonized land-use estimates for photovoltaics (PV) and concentrated solar power (CSP).

Solar technology	Direct Land-Use (m^2 MWh^{-1} yr)				Total land-use (m^2 MWh^{-1} yr)
	Median	Min	Max	n	
CSP-Tower	10.4	10.4	10.4	1	14.6
CSP-Trough	8.9	8.9	8.9	1	12.5
PV (Fixed tilt/Flat-Plate)	6.7	5.7	13.5	5	9.4
PV (1-axis)	7.6	7.6	7.6	1	10.6
CPV	6.7	4.7	6.7	3	9.4

Table 7
Variability in performance parameters reported in literature.

Solar technology	Parameters	Values			
		High water use	Low water use	High land use	Low land use
CSP	DNI (kWh m^{-2} yr^{-1})	2592	2940	2700	2900
CSP	LT (years)	30	30	30	30
CSP	SE (%)	11	16	8.5	10.7
PV	DNI (kWh m^{-2} yr^{-1})	900	2592	1770	2400
PV	LT (years)	25	30	30	60
PV	ME (%)	12.2	14	N/A	N/A
PV	PR (%)	0.53	0.93	N/A	N/A
PV	SE (%)	N/A	N/A	9.5	10.6
CPV	DNI (kWh m^{-2} yr^{-1})	2592	2592	2500	2500
CPV	LT (years)	25	25	30	30
CPV	SE (%)	16	16	13.8	20.2

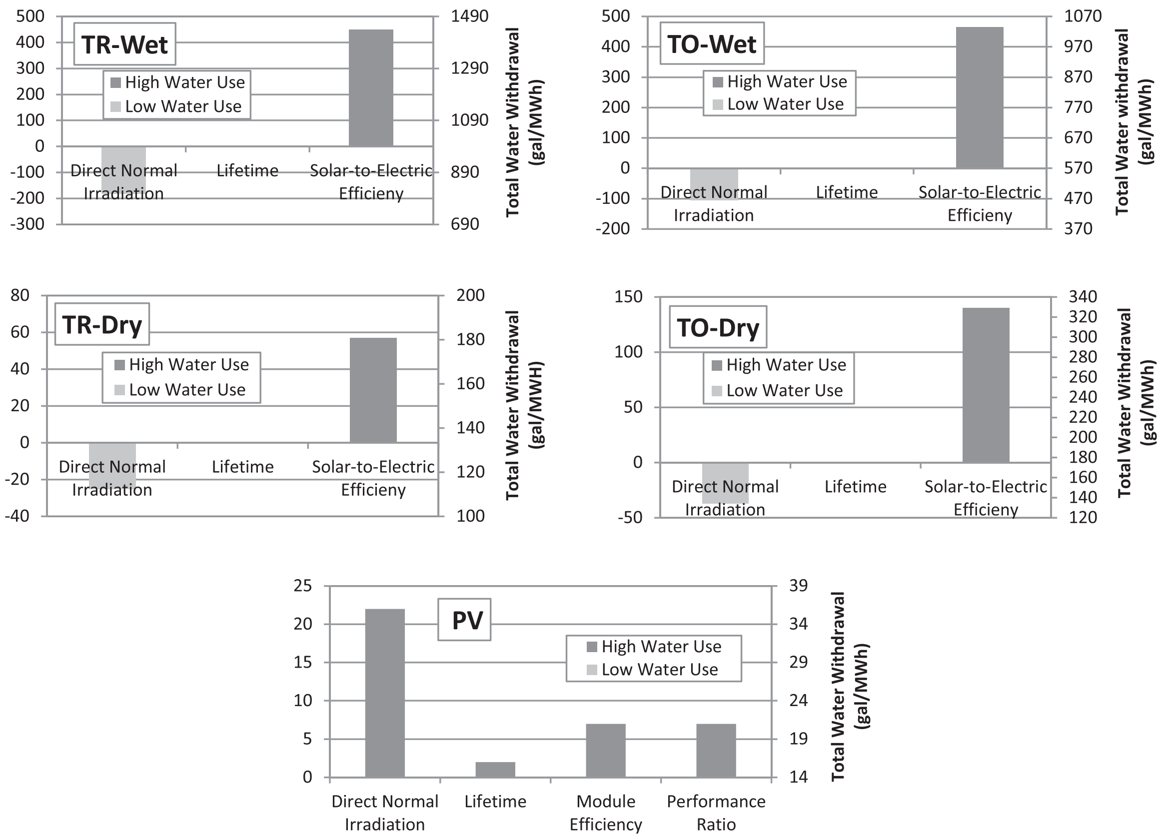

Fig. 3. Sensitivity analysis to represent the variation of median water use estimates for solar photovoltaic (PV), Tower wet-cooling (TO-Wet), Tower dry-cooling (TO-Dry), Trough wet-cooling (TR-Wet), and Trough dry-cooling (TR-Dry), across a range of performance parameters.

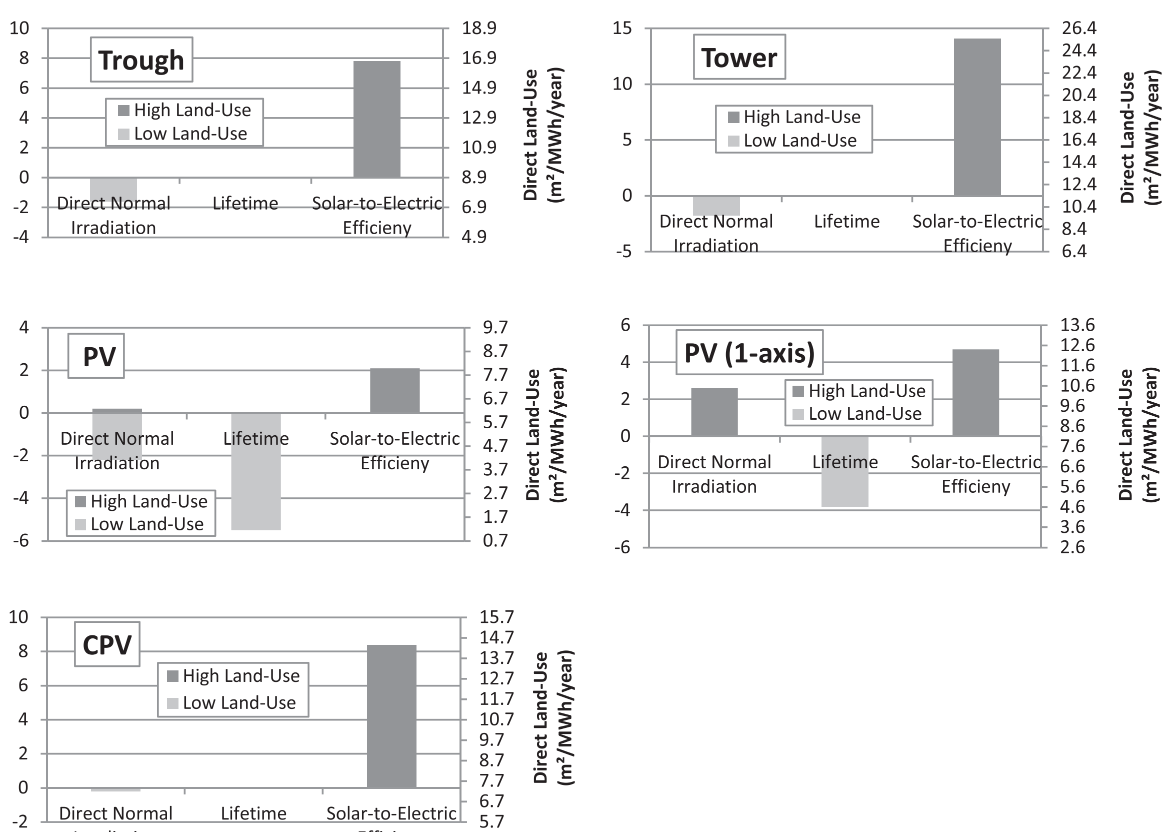

Fig. 4. Sensitivity analysis to represent the variation of median land use estimates for solar photovoltaic (PV), concentrated photovoltaic (CPV), power tower and parabolic trough, across a range of performance parameters.

less than 0.5 gal MWh^{-1} for both PV and CSP technologies (Table 5). Hence, the impact of dismantling a power plant on water resources is smallest compared to construction and operational water requirements.

Land use estimates were developed based on the dataset provided by [84]. The harmonized estimates for land-use intensity are shown in Table 6. Direct land is the area occupied by solar infrastructure, whereas total land is the fenced area of a solar facility. Total land area is approximately 1.4 times the direct land area for both PV and CSP systems [45]. Since most studies report total land estimates, both direct and total land-use intensities were estimated in the current study. Land use requirements were found to be smallest for PV and CPV technology and largest for CSP-tower. Using larger dataset for harmonization may lead to better approximation of land use estimates for solar systems.

Sensitivity analysis of the harmonized estimates was also performed to depict the variation of median water and land use estimates across various performance parameters. Extremes reported in the literature for various performance parameters were used to perform the sensitivity analysis (Table 7). Median water withdrawal and direct land-use estimates for various solar technologies were considered. The analysis resulted in low and high water and land use estimates, compared to the median estimates, as shown in Fig. 3 and Fig. 4. The results show the sensitivity of the water and land use estimates to operational or design parameters and the extent of their variation. For example, decreases in solar-to-electric efficiency or direct normal irradiation levels would result in higher water use estimates in units of gal MWh^{-1} and higher land-use estimates in units of $m^2 MWh^{-1} yr$.

Approximations for median water and land use estimates for various utility-scale solar-plant configurations were incorporated into the simulation model. Model validation was achieved by comparing the results generated in this study to published literature. Comparisons were drawn between water required for operational process generated from the simulation model developed in the current study and the operational water computations by [98,99]. Comparisons were also drawn between total land use estimates generated by the simulation model and the land-use estimates reported by [45,98]. As shown in Table 8, the model estimates are in good agreement with the results of these studies.

5.2. Simulation Modeling

Total water and land-use estimates generated for various configurations of PV and CSP technologies in Section 5.1 were incorporated into the simulation model to compute RPS-based water and land demands. These were compared to the water and land resources available within the 19 SEZs of the six states for the deployment of utility-scale solar power, based on the RPS/RPG of the six states between 2015 and 2030 (Figs. 5–10). Total water was the sum of water required during construction, operation, and dismantling of the solar plant. Total on-site water withdrawals for tower wet cooling, tower dry cooling, trough wet cooling and trough dry cooling were found to be 570, 180, 990, and 130 gal MWh^{-1}, respectively; water consumption was found to be 530, 140, 910, and 81 gal MWh^{-1} (Table 5). Total water use estimates for PV and CPV were found to be 14 and 19 gal MWh^{-1} (Table 5). Direct land use was 1.4 times smaller than total land use [45]. Comparisons with the available land were drawn against the total land requirements of solar installations.

5.2.1. RPS-based water and land demands and availability

When analyzing the contribution of SEZs, RPS/RPG based support was analyzed in increments of 5%; 1% increments were used for SEZs for which the RPS/RPG based support was less than 5% support. Less than 1% RPS/RPG based support was not analyzed. Land demands were largest for CSP-tower, whereas water demands were largest for CSP trough wet cooling and represented as the extreme-case scenario when comparing availability versus demand. Results for the 19 SEZs in the six southwestern states are discussed as follows.

Table 8
Validation of the simulation model by comparing water use and land use results against published literature.

S.N.	Project name	Type	Size (MW)	Cooling method	Generation ($MWh\ yr^{-1}$)	[98] Operational water use ($\times 10^3 m^3 yr^{-1}$)	[22] Operational water use ($\times 10^3 m^3 yr^{-1}$)	This Study Operational water use ($\times 10^3 m^3 yr^{-1}$)	[98] Land use ($\times 10^6 m^2$)	[45] Land use ($x10^6 m^2$)	This study land use ($\times 10^6 m^2$)
1.	Quartzite - AZ	CSP Tower	100	Dry	450,000	246.7	44.3	221.4	6.8	5.8	6.5
2.	Abengoa Mojave-CA	CSP Trough	250	Wet	600,000	2664.3	2057.8	2044	7.1	9.5	7.4
3.	Genesis - CA	CSP Trough	250	Dry	600,000	268.9	177	160	7.9	9.5	7.4
4.	McCoy Solar-CA	PV-(1-axis)	750	–	1,708,200	54.3	6.5	58.2	18.2	22.8	18.1
5.	Solar One - NV	CSP Trough	64	Wet	134,000	493.4	459.6	456.5	1.6	2.1	1.7

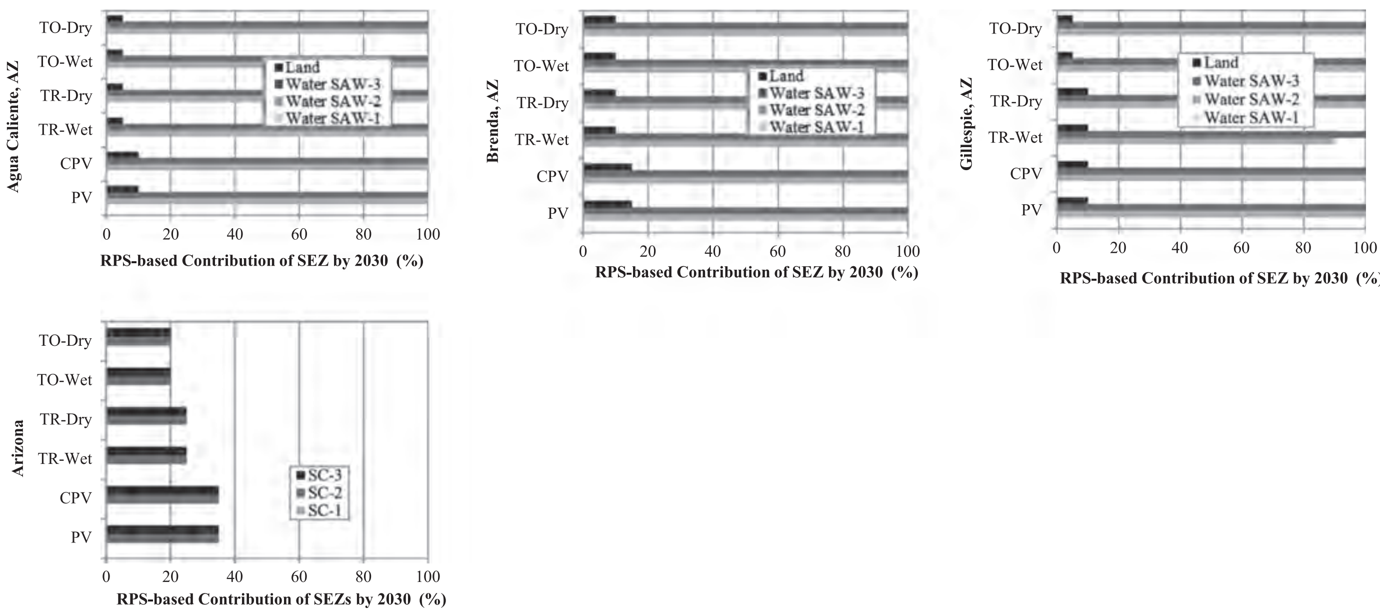

Fig. 5. Contribution of Arizona and its solar energy zones (Agua Caliente, Brenda and Gillespie) to fulfill renewable portfolio standards of the state for various solar technologies of solar photovoltaic (PV), Tower wet-cooling (TO-Wet), Tower dry-cooling (TO-Dry), Trough wet-cooling (TR-Wet), and Trough dry-cooling (TR-Dry).

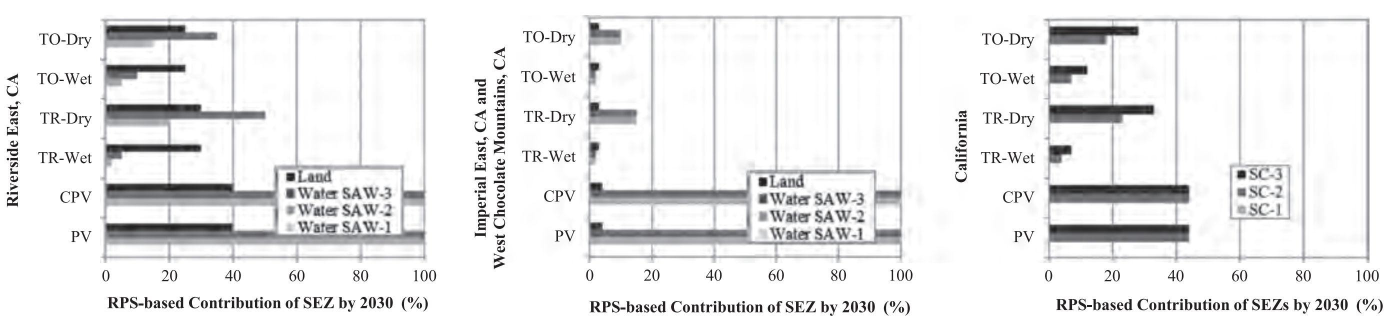

Fig. 6. Contribution of California and its solar energy zones (Riverside East, Imperial East, West Chocolate Mountains) to fulfill renewable portfolio standards of the state for various solar technologies of solar photovoltaic (PV), Tower wet-cooling (TO-Wet), Tower dry-cooling (TO-Dry), Trough wet-cooling (TR-Wet), and Trough dry-cooling (TR-Dry).

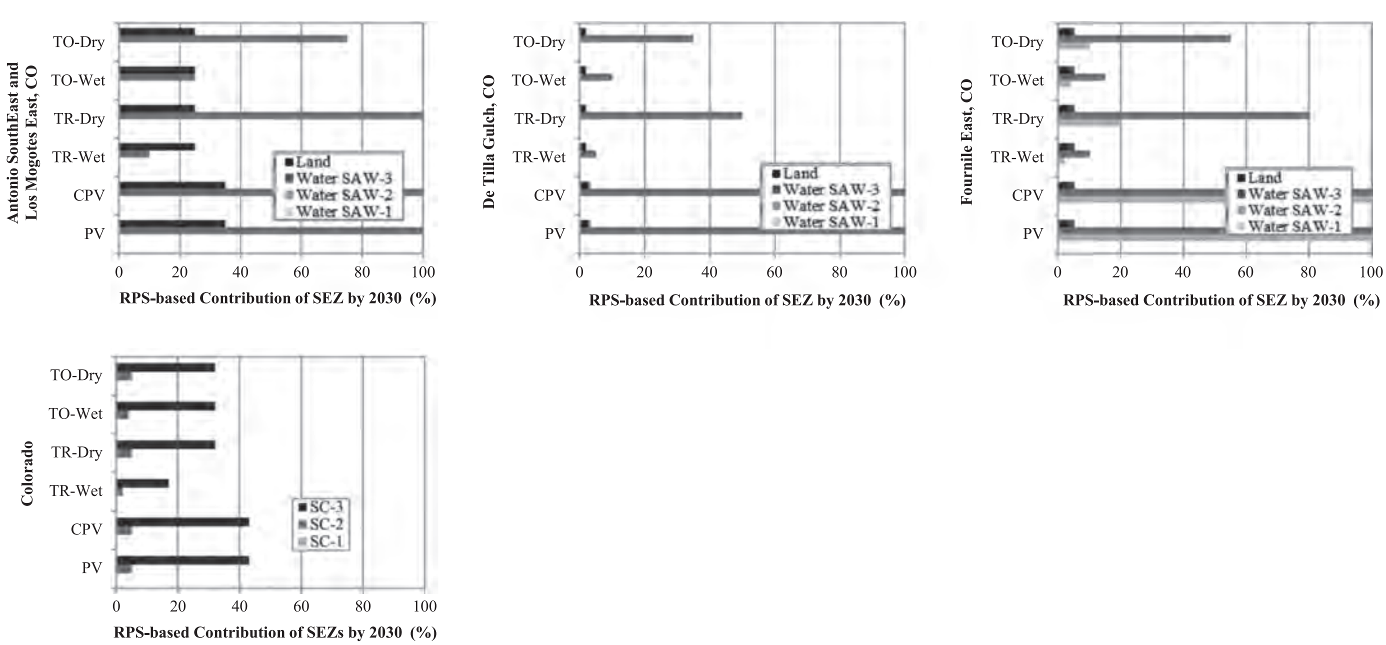

Fig. 7. Contribution of Colorado and its solar energy zones (Antonio Southeast, Los Mogotes East, De Tilla Gulch, Fournile East) to fulfill renewable portfolio standards of the state for various solar technologies of solar photovoltaic (PV), Tower wet-cooling (TO-Wet), Tower dry-cooling (TO-Dry), Trough wet-cooling (TR-Wet), and Trough dry-cooling (TR-Dry).

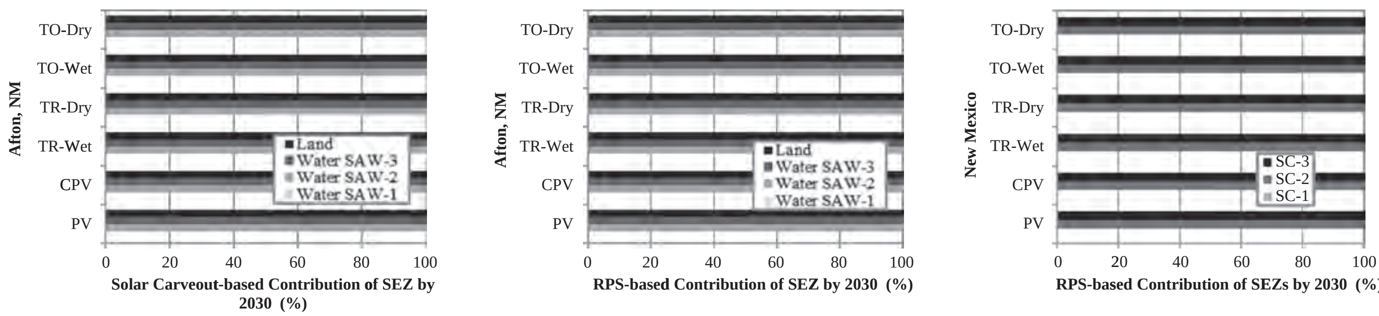

Fig. 8. Contribution of New Mexico and its solar energy zone (Afton) to fulfill renewable portfolio standards of the state for various solar technologies of solar photovoltaic (PV), Tower wet-cooling (TO-Wet), Tower dry-cooling (TO-Dry), Trough wet-cooling (TR-Wet), and Trough dry-cooling (TR-Dry).

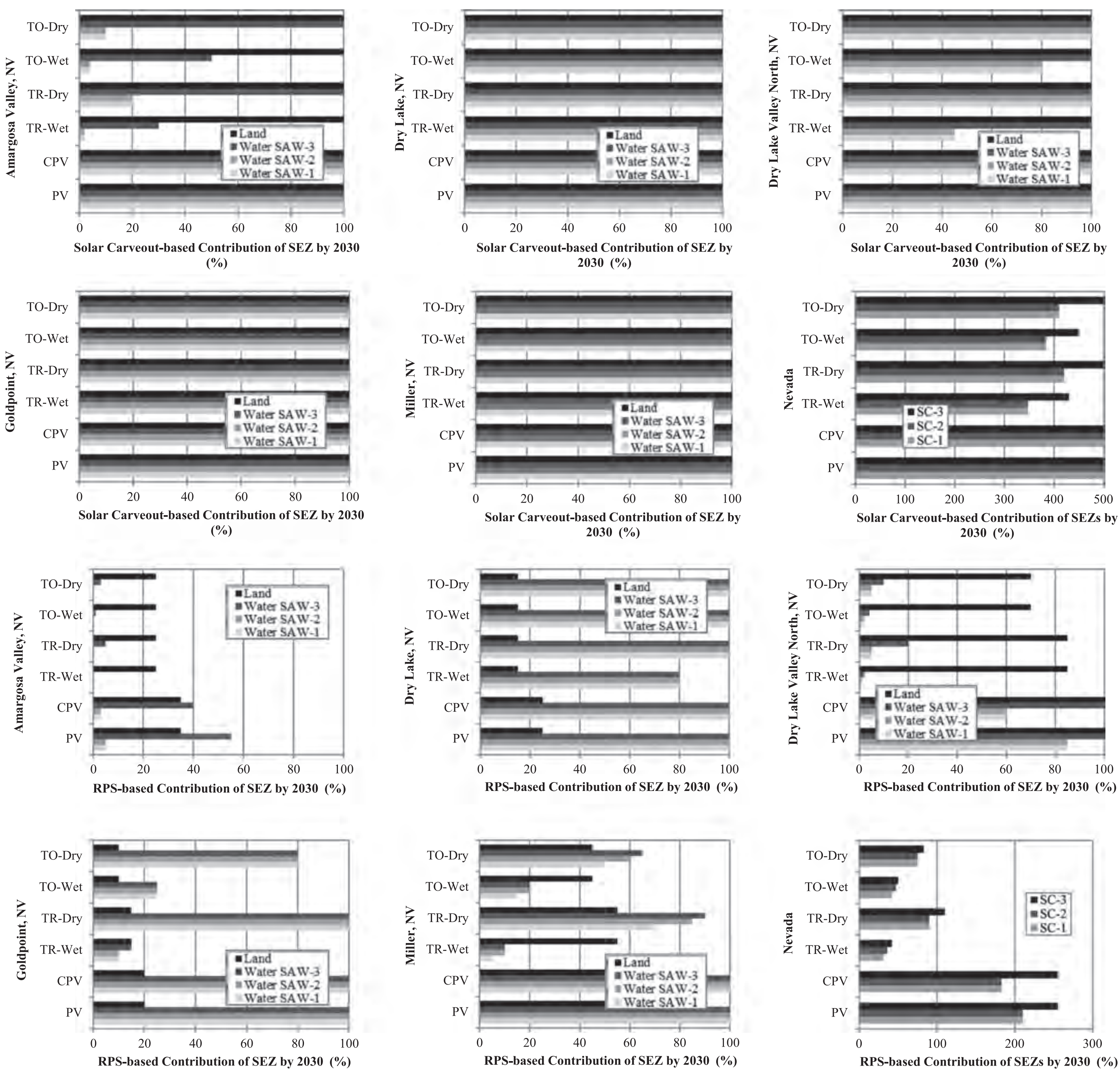

Fig. 9. Contribution of Nevada and its solar energy zones (Amargosa Valley, Dry Lake, Dry Lake Valley North, Goldpoint, Miller) to fulfill renewable portfolio standards of the state for various solar technologies of solar photovoltaic (PV), Tower wet-cooling (TO-Wet), Tower dry-cooling (TO-Dry), Trough wet-cooling (TR-Wet), and Trough dry-cooling (TR-Dry).

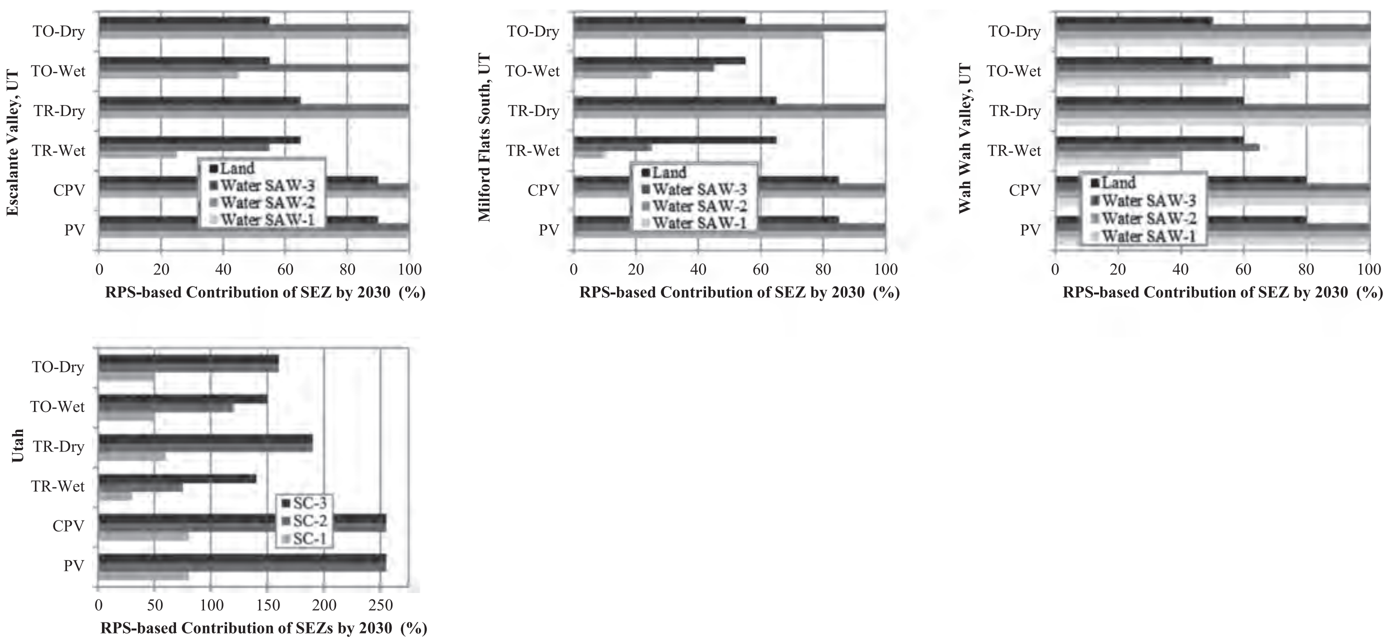

Fig. 10. Contribution of Utah and its solar energy zones (Escalante Valley, Milford Flats South, Wah Wah Valley) to fulfill renewable portfolio standards of the state for various solar technologies of solar photovoltaic (PV), Tower wet-cooling (TO-Wet), Tower dry-cooling (TO-Dry), Trough wet-cooling (TR-Wet), and Trough dry-cooling (TR-Dry).

Arizona did not contain any UGW or USW resources within their three SEZs (Table 1, Fig. 2, Fig. 5). The RPS of Arizona stipulates that 15% of total electricity retail sales in the state must be met by renewables by 2025; it does not have any standards specifically with regard to solar deployment (Table 2). If 15% of the total electricity retail sales, or in other words 100% of the RPS requirements for Arizona, were to be met by means of utility-scale solar installations in the SEZs, model simulations showed that SAW-2 and SAW-3 scenarios (i.e., the resources of AW, BGW, and WW) were sufficient to meet solar water demands between the years 2015–2030. Arizona has large quantities of BGW resources within the three SEZs, totaling approximately 219.33 million m^3 per year (Table 1, Fig. 2). Making use of this resource warrants desalination and would incur additional construction and operational costs since desalination is an energy intensive process [42]. The SEZs of AZ have ample water resources for the scenarios of SAW-2 and SAW-3. However, when considering the land availability of SEZs of AZ, RPS-based contribution of Agua Caliente and Brenda SEZs for CSP systems (trough and tower) was 5% and 10%, and for PV/CPV systems was 10% and 15%, respectively, by the year 2030 as shown by Fig. 5. Gillespie SEZ can only support 5% of RPS for power tower whereas PV, CPV, and trough systems can support up to10% of RPS by the year 2030 as shown by Fig. 5. Overall contribution of the three SEZs of AZ to support the RPS of the state was 20% for tower, 25% for trough and 35% for PV and CPV technologies (Fig. 5)

For California, 50% of their electricity production must be achieved by using renewable energy by 2030 (Table 2); the RPS does not stipulate any standards for solar power development. Hence, the various scenarios were generated as a percentage of the RPS. Based on [40], regarding data on water availability, UGW or USW resources were not available for the three SEZs in California. In addition, results showed that water demands of PV and CPV technology were small enough that water availability estimates for the SAW-2 and SAW-3 scenarios were sufficient even if the entire RPS requirements of California (i.e., 50% of CA electricity production) was to be met by using PV and CPV systems (Fig. 6). However, because of limitations presented by the land availability of the SEZs, only 4% of RPS can be supported by Imperial East and West Chocolate Mountains and 40% of the RPS for Riverside East if PV/CPV technologies were deployed. Furthermore, about 2% of RPS may be fulfilled by using wet cooling technologies in Imperial East and West Chocolate Mountains. Overall, SEZs of California can support RPS in the range of 28–33% for dry cooling technologies, 7–12% for wet cooling technologies, and 44% of the RPS if PV/CPV technologies were to be deployed.

For Colorado, UGW, USW, and WW resources were not available within the three SEZs of Antonio Southeast, Los Monotes and De Tilla Gulch. However, the combined sum of AW and BGW for the three SEZs was enough to meet 100% of the RPS requirements for PV and CPV systems (Fig. 7). BGW (1.38 million m^3 yr^{-1}) was available only for SEZ Fournile East (Fig. 2), whereas AW availability was 15.02 million m^3 yr^{-1} [40] for the other three SEZs in Colorado. Hence, the development of solar installations within the SEZs of Colorado is dependent largely upon the transfer or abandonment of existing water rights to meet water demands for solar energy. Overall, considering both water and land availability, the SEZs of Colorado can support up to 5% and 2% of RPS for SC-2 and 43% and 17% of RPS for SC-3 for PV and trough wet cooling, respectively.

For New Mexico, UGW and USW resources were not available within SEZ Afton for HUC-8 region of 13030102. However, BGW resources were sufficient (34.54 million m^3 yr^{-1}) to meet the water requirements of the solar carve-out for New Mexico's RPS (Fig. 8). In addition, 100% of RPS requirements could be met by using solar installations within Afton, using any configuration of solar technology, when considering both land and water availability for the scenarios of SC-2 and SC-3 (Fig. 8). For successful deployment of solar facilities, Afton would have to rely heavily on desalination of BGW to meet water requirements.

The availability of UGW resources for Nevada was the highest for the Dry Lake SEZ located within the 15010012 HUC 8 region, in the amount of 28.34 million m^3 yr^{-1} (Fig. 2), and lowest for Amargosa Valley SEZ located within 18090202 HUC 8 region, in the amount of 0.02 million m^3 yr^{-1}. BGW resources were available only for Dry Lake (1.38 million m^3 yr^{-1}), whereas WW resources only were available for Millers (0.76 million m^3 yr^{-1}). Results for Nevada showed that enough water and land resources were available within the SEZs to meet the water and land demands of the solar carve-out of the Nevada RPS; 100% of the RPS requirements within Nevada potentially could be met by means of solar PV, CSP-Trough dry cooling and CSP-tower dry cooling technology within each of the SEZs for scenario SC-1, SC-2 and SC-3 (Fig. 9). Overall, PV systems could potentially fulfill over 200% of RPS-based requirements, when considering all 5 SEZs. Compared to other technologies, overall, deployment of CSP trough wet cooling provided the lowest levels of RPS-based support, which were 31%, 36%, and 42% of the RPS requirements for scenarios SC-1, SC-2 and SC-3, respectively.

For Utah, UGW resources only were available for Wah Wah Valley within the 16030009 HUC-8 region. AW resources for the three SEZs were 7.37 million m^3 yr^{-1}. Solar PV and CPV could potentially be used to meet 80% of the RPG requirements, based on land and water availability estimates for SC-1, whereas trough wet cooling can support up to 30% of RPG requirements (Fig. 10). As shown by Fig. 10, overall, sufficient water and land resources were available within the three SEZs to support over 100% of the RPG requirements, using any configuration of solar technology, for the scenarios of SC-2 and SC-3 with the exception of trough wet cooling systems for SC-2 (75% of RPG requirements).

These results have certain policy implications as well. The development of solar power in these zones may be curtailed due to limited availability of water, and these results show that the bridge between the regional energy policy makers and the water sector may be missing. SEZS were created to promote solar power in the southwest, where solar insolation levels are some of the highest worldwide. However, the results showed that unappropriated water availability was an issue for most of the SEZs, especially for deployment of water-intensive CSP technologies [23,99–101]. USW resources were not available for any of the 19 SEZs; UGW resources were also unavailable for the SEZs within AZ, CA, CO, and NM. The lack of solar power development standards in AZ, CA, and CO's state RPS may limit the development of solar power in the SEZs of these states. Even though USW resources were not available, BGW resources in the Afton SEZ of NM were sufficient to meet the water requirements of the solar carve-out as well as 100% of RPS requirements. Still, solar deployment in Afton SEZ may have to rely on BGW resources that require water desalination, thus adding expenditure and hindering the promotion of solar power in that area. Existing water rights can be bought from one use to another [39], but the option may not always be available. Water can also be transported to the site, but again, this demands additional costs [41].

Solar Energy Environmental Mapper [102] revealed that none of the utility-scale solar projects exist within the boundaries of SEZs except those in California. Riverside East SEZ was shown to have one operational solar facility, while three were under-construction. West Chocolate Mountains SEZ was shown to have 2 solar facilities under construction. There is a lack of interest being shown by the investors in utilizing SEZs for utility-scale solar development, and one of the reasons maybe due to limited availability of water.

The southwest U.S. is also one of the driest regions in the country and is currently facing a severe multi-year drought [103]. [104] predicted a decrease in global groundwater recharge under the climate-change scenario. Various studies have projected a warmer and drier climate under changing climate scenarios for the region [105,106], as well as longer and more intense droughts [4]. Water demands are expected to increase under the changing climate and growing population in the southwest [107]. As a result, water availability in the SEZs may decrease even further under climate change scenario, another cause of concern for successful implementation of policies regarding solar in the region.

Furthermore, results show that some SEZs may have little or no water especially when considering unappropriated water resources (Fig. 2). Additional costs involved for water treatment or water conveyance to the site of solar deployment may render such SEZs an unattractive prospect to investors. For successful enforcement of solar energy policies in the southwest, local ground realities with regards to water availability need to be considered. Unappropriated water availability should be an important consideration when identifying SEZs. There needs to be convergence between energy policy makers and the water sector [108]. Various policies have been established to support solar PV and CSP [109,110], but understanding the nexus between solar energy and water is crucial for promotion of solar energy in the water-limited region.

As seen by the results, solar PV was determined to be a feasible choice for most of the water-deficient SEZs in the southwestern U.S. based on the demand and availability of water and land resources. [111] explored the usage of solar PVs between 2010 and 2050, based on water availability in the U.S. and cost feasibility. They determined that PV was a viable option for energy generation in the U.S. To meet 31,721 MW of capacity in the six southwestern states by 2030, [23] estimated the water demand for wet cooling to be 272.9 million m^3, compared to 22 million m^3 when estimating water demands for dry cooling. However, the implementation of RPS also leads to water-usage reductions, as shown by [112], who estimated reductions in water withdrawals and consumption to be 3.14 billion m^3 and 102.2 million m^3, respectively, in 2013, based on the RPS implementation in 29 states and Washington, D.C. [113] explored the use of reclaimed water as an alternative source of water supply for SEZs and found it to be an effective option for most of the SEZs if solar PV was deployed.

In the case of land shortages, PV and CPV technology might be feasible options as the land-use requirements for these technologies were found to be the smallest. Similar findings have been made by other studies as well. [114] analyzed land usage of PV and biomass for energy production and determined PV to have better potential for energy generation. [8] analyzed land usage of utility-scale PV and CSP, among other renewables, by using a simulation model known as the Regional Energy Deployment System (ReEDS). It was assumed that 80% of the electricity demand of the U.S. could be met by means of renewables by 2050. The study estimated 5900 km^2 of land usage by PVs (panels and inverters), based on a land-use factor of 50 MW km^{-2}, and 2900 km^2 of land usage for CSPs (mirrors only) for a land-use factor of 31 MW km^{-2}. [44] analyzed the land usage of solar PV for the generation of electricity and found that approximately 0.6% of the land area in the U.S. could be used for PV solar installations to meet the U.S. electricity demand for 2005. Their study calculated the per capita solar PV footprint for Arizona (145 m^2 $person^{-1}$), California (119 m^2 $person^{-1}$), Colorado (142 m^2 $person^{-1}$), New Mexico (114 m^2 $person^{-1}$), Nevada (137 m^2 $person^{-1}$), and Utah (128 m^2 $person^{-1}$), among other states [44]. [115] determined that solar PV generated the least effects to land when compared with other renewables (CSP technology, wind, hydropower, and biomass) as well as with traditional electricity generation technologies (natural gas and nuclear). [116] determined land requirements for forty countries, under the assumption that solar energy was used to fulfill 100% of the countries' energy requirements. The study determined that this scenario was not feasible for countries (Japan and European Union countries) where land requirements were $\geq$ 50% of current unused land, but feasible for countries such as Canada and Australia where land requirements were < 1%. [117] analyzed 10% of contaminated or degraded land areas in the U.S. for deployment of renewables, based on RPS, and found them to be sufficient to meet RPS-based demands.

Solar technology has come a long way since its inception, resulting in efficient and cost effective PV and CSP systems, thus leading to their increased popularity for energy generation [118–122]. Ongoing research regarding PV technologies is focused on different areas, including minimizing efficiency losses and discovering higher efficiency solar cell materials that can be manufactured cost-effectively on a commercial scale. Overall, efficiency of CSP systems depend on the heat collection and heat conversion processes. Innovations have been made in the field of CSP technology by using improved materials and design methodologies for heat collection, heat conversions, power production and thermal energy storage systems [123–126]. Continued research will lead to further improvements and more efficient and cost effective solar systems in the future [126–128]. Improvements in efficiency will result in reduced usage of water and land for solar deployment.

PV technology was found to be the most feasible based on water and land demands for scenario SC-1, SC-2, and SC-3, for the 19 SEZs as shown by Figs. 5–10, making PV and CPV technology an ideal option for water stressed regions as well for supporting solar promotion in the southwest. CSP technologies were the most intensive when considering both land and water usage and availabilities. CSP-Trough wet cooling technology was found to be the least feasible technology when considering the scenarios of SC-1, SC-2, and SC-3, except in the case of Arizona; CSP-Tower wet cooling technology was found to be the least feasible when considering both land and water demands in Arizona.

The model simulations were based on the assumption that each solar technology fulfilled 100% of the scenario requirements for every model run. In reality, the solar deployments likely would be a mix of different configurations of solar technologies. However, this study might help identify those solar technologies whose deployment most likely could benefit regions with limited water or land available for solar energy.

5.2.2. Carbon emissions

Net carbon emissions were analyzed based on the results of scenario SC-3 for the six southwestern states of AZ, CA, CO, NM, NV and UT, for PV and CSP technology. Solar PV could potentially support of 35%, 44%, 43%, 100%, 255% and 255% of RPS/RPG requirements in AZ, CA, CO, NM, NV and UT, respectively for SC-3 scenario. Comparatively, CSP technology could support 20%, 7%, 17%, 100%, 42% and 140% of RPS/RPG requirements in AZ, CA, CO, NM, NV and UT, respectively (Section 5.2.1).

Net reduction in carbon emissions for solar PV was found to be 1.35, 14.5, 3.99, 3.44, 11.02 and 6.43 billion kg$C0_2$eq, for AZ, CA, CO, NM, NV and UT, respectively, for scenario SC-3. These measurements are equivalent to GHG emissions from 0.28, 3.06, 0.84, 0.73, 2.33 and 1.36 million passenger vehicles driven for one year. The equivalency was calculated using the Greenhouse Gas Equivalencies Calculator developed by the Environmental Protection Agency (EPA) [129]. Net reduction in carbon emissions for CSP systems was found to be 0.81, 2.56, 1.64, 3.55, 1.82 and 3.63 billion kg$C0_2$eq for AZ, CA, CO, NM, NV and UT, respectively, for scenario SC-3; this corresponds to about 60%, 18%, 41%, 103%, 17% and 57% of the reductions achieved through the deployment of PV technology. Results for net reduction in carbon emissions showed the use of solar technology in place of the current energy-source mix for electricity generation could lead to a tremendous carbon offset for all six states.

Similar results were found by other studies. The New York State Energy Research and Development Authority (NYSERDA), which oversees and executes the implementation of the New York RPS, analyzed reductions in harmful emissions for New York State between 2006 and 2014. They reported a reduction of 6.08 million kg of nitrogen oxide, 11.07 million kg of sulfur dioxide, and 5.81 billion kg of CO_2 [130]. The RPS for New York State stipulates that 29% of their electricity consumption should be met by using renewables by 2015 [83]. [131] generated a carbon-intensity simulation and showed that the implementation of RPSs in the U.S. between 1997 and 2010 reduced the carbon emissions by 4% nationwide.

[132] modeled a simulation that incorporated 49 policies related to target reductions in carbon emissions in California from 2010 to 2050, and reported that the targets for 2020 met reductions in carbon emissions of 387.4 billion kg CO_{2eq} yr^{-1}. For 2030, a reduction in carbon emissions was found to be between 191.4 and 387.4 billion kg CO_{2eq} yr^{-1}, indicating the significance of present policies regarding future emissions. Reductions in emissions by 2050 were lower than the target goal of 387.4 billion kg CO_{2eq} yr^{-1} and were estimated to be 77.1 billion kg CO_{2eq} yr^{-1}, indicating the need for additional, and more robust, policies. [112] estimated a reduction in GHG emissions of 53.5 billion kg CO_{2eq} by 2013, due to the implementation of RPSs in 29 states and Washington, DC. [133] determined a 69–82% reduction in carbon emissions if 80% of electricity is generated using renewable energy by the year 2050 for United States.

6. Conclusion

The objectives of this study were to (a) generate harmonized water consumption and land estimates for solar energy installation in the southwestern US; and (b) to make quantitative assessments of water and land usage and their availability for utility-scale solar deployment, based on the renewable portfolio standards (RPS) of six southwestern US states between by generating a simulation model.

The current study generated harmonized water (construction, operation and dismantling) and land use (direct and total) estimates using the parameters relevant to the southwestern US. The following was concluded from the study:

- Based on harmonized estimates, CSP trough wet-cooling technology was shown to have the largest effect with respect to water demands, whereas PV technology had the least effect, among the various configurations of technologies analyzed.
- Based on harmonized estimates, CSP-tower had the largest effect with respect to land requirement, whereas solar PV and CPV had the smallest effect.
- Solar PV was shown to be favorable for areas with limited water or land resources.

Furthermore, the study developed a simulation model to quantitatively assess water usage and its availability, land usage and availability, and associated reductions in carbon emissions for utility-scale solar deployment, based on the renewable portfolio standards within the nineteen solar energy zones of six southwestern states – Arizona, California, Colorado, Nevada, New Mexico, and Utah – between 2015 and 2030. The following was concluded:

- There was no USW resource available for any of the 19 SEZs. However, UGW resources were available for some of the SEZs within Nevada and Utah. Moreover, solar deployment within the SEZs of Arizona, California, Colorado, and New Mexico would have to rely on AW, BGW and WW resources. Adopting BGW as a water resource would require water treatment using desalination plants, whereas using WW as a water resource would require the construction of reclamation facilities, both of which render additional costs. Limited availability of unappropriated water may hinder the development of utility-scale solar power in the SEZs. Convergence between energy policy makers and the water sector is crucial for sustainable development in the region.
- Nevada and New Mexico have policies regarding solar as a part of their RPS/RPG; Arizona, California, Colorado, and Utah do not have such policies. Total water (including reclaimed and desalinated water) and land resources within the SEZs may be sufficient for utility-scale solar deployment to meet the solar carve-outs of Nevada and New Mexico RPS.
- Based on the availability of total land and all the water resources within the SEZs, solar energy zones in Arizona, California, Colorado, New Mexico, Nevada, and Utah potentially could support 20%, 7%, 17%, 100%, 42% and 140% of RPS/RPG requirements, respectively, assuming use of CSP wet cooling systems.
- Based on the best case scenario of PV technology, solar energy zones of Arizona, California, Colorado, New Mexico, Nevada, and Utah potentially could support 35%, 44%, 43%, 100%, 255% and 255% of RPS/RPG requirements, respectively, when considering total water and land demands and availabilities.
- Overall, solar PV technology was shown to be a feasible option for electricity generation within water-limited or land-limited areas.
- Using solar technology instead of continuing with the current energy-source mix for electricity generation could lead to a tremendous carbon offset for all six states in the southwestern US
- A greater understanding of solar energy-water nexus, especially on a local scale, is crucial for successful implementation of energy

policies and avoidance of water-limited zones becoming a hindrance to solar energy development in the region.

These model simulations were based on the assumption that each solar technology fulfilled 100% of the scenario requirements for every model run. The conclusions were drawn using extreme case scenarios. In reality, the solar deployments would likely be a mix of different configurations of solar technologies. The composition of the future energy mix for solar technologies is not available, but such data may lead to a more reliable analysis and improved policies regarding solar in the region. Regardless, results of this study could help identify the solar technologies whose increased deployment could likely benefit water-limited or land-limited regions. Utilizing solar power for electricity production would lead to tremendous carbon offsets, as indicated by the results.

In terms of future research, using an energy mix of solar technologies in the southwest will provide a more reliable analysis of regional solar energy-water nexus as well as aid in improving the policies meant to promote solar power in the region. Furthermore, the simulation model generated in this study could be used to analyze and compare the performances of other renewable energy sources in addition to solar energy. Moreover, this model could be replicated for other regions, using data applicable to those regions.

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