University Libraries
University of Nevada, Las Vegas

UNLV Theses, Dissertations, Professional Papers, and Capstones

May 2018

Water-Energy Nexus Approaches for Solar Development and Water Treatment in the Southwestern United States

Syeda Saria Bukhary
BUKHARY477@YAHOO.COM

Follow this and additional works at: https://digitalscholarship.unlv.edu/thesesdissertations

Part of the Civil Engineering Commons

Repository Citation
Bukhary, Syeda Saria, "Water-Energy Nexus Approaches for Solar Development and Water Treatment in the Southwestern United States" (2018). *UNLV Theses, Dissertations, Professional Papers, and Capstones*. 3224.
https://digitalscholarship.unlv.edu/thesesdissertations/3224

This Dissertation is brought to you for free and open access by Digital Scholarship@UNLV. It has been accepted for inclusion in UNLV Theses, Dissertations, Professional Papers, and Capstones by an authorized administrator of Digital Scholarship@UNLV. For more information, please contact digitalscholarship@unlv.edu.

المنارة للاستشارات

www.manaraa.com

WATER-ENERGY NEXUS APPROACHES FOR SOLAR DEVELOPMENT AND WATER TREATMENT IN THE SOUTHWESTERN UNITED STATES

By

Syeda Saria Bukhary

Bachelor of Engineering
NED University of Engineering and Technology
2003

Master of Engineering
NED University of Engineering and Technology
2006

Master of Science
University of Nevada, Reno
2012

A dissertation submitted in partial fulfillment
of the requirements for the

Doctor of Philosophy in Engineering - Civil and Environmental Engineering

Department of Civil and Environmental Engineering and Construction
Howard R. Hughes College of Engineering
The Graduate College

University of Nevada, Las Vegas
May, 2018

© Copyright 2017 Syeda Saria Bukhary

All rights reserved

UNLV | GRADUATE COLLEGE

Dissertation Approval

The Graduate College
The University of Nevada, Las Vegas

January 25, 2018

This dissertation prepared by

Syeda Saria Bukhary

entitled

Water-Energy Nexus Approaches for Solar Development and Water Treatment in the Southwestern United States

is approved in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Engineering - Civil and Environmental Engineering
Department of Civil and Environmental Engineering and Construction

Sajjad Ahmad, Ph.D.
Examination Committee Chair

Jacimaria Batista, Ph.D.
Examination Committee Member

Yahia Baghzouz, Ph.D.
Examination Committee Member

Haroon Stephen, Ph.D.
Examination Committee Member

Ashok Singh, Ph.D.
Graduate College Faculty Representative

Kathryn Hausbeck Korgan, Ph.D.
Graduate College Interim Dean

المنارة للاستشارات
www.manaraa.com

ABSTRACT

Water is crucial for energy production and conversion, and energy is crucial for various water related processes including water conveyance, treatment and distribution. Sustainability of water and energy are inextricably linked with each other. Over-utilization/ degradation of these resources may occur due to limited availability of water under the changing climate scenario, growing population, and increasing pollution due to the burning of fossil fuels. The goal of the current research was to study the water-energy nexus of the Southwestern U.S. and develop approaches for solar development and treatment of drinking water. To achieve the overall objective, the work was divided into two main research tasks.

Research task 1 addressed the water demands and availability issues for utility-scale solar development in six southwestern states to meet the target goals of their renewable portfolio standards (RPS) between the years of 2015-2030. Solar energy-water nexus was analyzed for the southwestern states of Arizona, California, Nevada, Colorado, New Mexico and Utah. Estimates were gathered for water withdrawal and consumption (related to plant construction, operations, and dismantling) and land use (direct and total) for solar technologies of concentrated solar power and solar photovoltaics (PV), 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 nineteen solar energy zones (SEZs) of six southwestern states based upon the 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. Further,

solar development led to tremendous reduction in carbon emissions in the region. Contributions of this study include a greater understanding of solar energy-water nexus, especially on a local scale, which is crucial for successful implementation of energy policies, by quantifying the effects of solar land and water demands on the resources of southwestern region. The generated model may be used as a screening tool for a crude assessment of future energy planning, solar project applications, and permit approvals. For future work, the generated model can be modified to analyze the performances of renewables in addition to solar.

Research task 2 involved the application of water-energy nexus approach for treatment of drinking water, which is an energy-intensive process and essential for safeguarding public health. Environmental impacts of the nexus are carbon emissions, which were reduced by using distributed solar to fulfill the energy requirements of three drinking water treatment plants (DWTPs), located in southwestern United States. The three plants differed by capacity (10 MGD, 90 MGD, 300 MGD), raw water source (groundwater, river, lake), and unit processes involved for treatment of raw water (in-line filtration, conventional filtration, direct filtration). Energy consumption was determined for various energy driving units. This, along with the existing acreage of the plant and economic feasibility; the DWTP was sized for solar photovoltaics. System Advisor Model was used for the performance and economic analysis of the solar system. Associated reduction in carbon emissions was also estimated. Energy intensity was determined as 153.7, 165.4, and 508.1 Wh m^{-3} for the small, medium and large DWTP, respectively. Pumping operation was determined to be the largest consumer of electricity for all three plants and utilized about 98%, 95%, and 90% of the total energy consumption for the 10 MGD, 90 MGD and 300 MGD plant, respectively. The development of solar PV for the three treatment plants was found to be economically feasible with positive NPV, with and without battery-storage systems. However, standalone solar PV development was not profitable for the 300 MGD DWTP for offsetting the total energy consumption. Further, the economic assessment was sensitive to changes in governmental incentives and financial parameters. Existing landholdings of the plants were sufficient for solar development. Moreover, change in geographic location from the southwest to east coast US, identified governmental incentives to affect the economic feasibility of PV systems. Contributions of this study include a successful application of the water-energy nexus approach for sustainable treatment of drinking water, by offsetting the fossil-fuel based energy consumption of three existing DWTPs by means of solar development. The design equations and results for the energy consumption can be applied to other plants utilizing similar processes. With the aim of incorporating sustainability in DWTPs in the southwestern U.S., the study provides a roadmap for using solar PV for DWTPs, leading to reduction in carbon emissions, energy costs and achieving energy independence.

ACKNOWLEDGEMENT

This work was supported by National Science Foundation under the Grant No. IIA-1301726.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

-

AW	-	Appropriated Surface Water/Groundwater
BGW	-	Brackish Groundwater
DR	-	Distributed Renewables
DWTP	-	Drinking Water Treatment Plant
LBL	-	Lawrence Berkeley Laboratory
NPV	-	Net Present Value
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

CHAPTER 1: INTRODUCTION

1.1 Introduction

Freshwater is essential for socio-economic development. Freshwater withdrawals are required for various processes including electricity generation, irrigation, mining and industrial activities, and domestic water use among others (Meldrum et. al., 2013; Maupin et. al., 2014; Rock 1998). Freshwater may also be used as a transport medium or as an outfall for pollution, resulting in the contamination of freshwater sources. Hence, spread of socio-economic development and elevated pollution levels coupled with growing population is ensuing scarcity of freshwater (von Medeazza, 2004; Vörösmarty et. al., 2000; Rock 1998).

With the growing population, water demand per capita also increases. It is estimated that by the year 2044, global population will reach 9 billion (U.S. Census Bureau, 2016a). According to a study by United Nations Organization (UNO), globally, by the year 2050, water demands are expected to increase by 55% (UNO, 2014a) and by the year 2025, two-thirds of the global population will be residing in water-stressed regions (UNO, 2015). Currently, over 1.7 billion of the world's population lives in regions where water withdrawal surpasses natural recharge (UN, 2015).

Water availability issues are also affected by the changing climate. Climate change may affect weather patterns related to temperature and precipitation causing extreme conditions of droughts and floods, thus disrupting the supply of water and affecting the availability and quality of water (Schewe et al. 2014; Arnell 2004; von Medeazza, 2004; Vörösmarty et al. 2000). The study by Schewe et al. (2014) predicts that a rise of 2.7°C above pre-industrial temperatures will affect 15% of the population with severe water scarcity. Limited water availability and pollution under climate change may contribute to the use of less quality water for freshwater production, requiring the use of new technologies for treatment of water such as nano-filtration, ultra-filtration, reverse osmosis, UV disinfection and ozonation. These technologies are energy-intensive, and may shift the energy trends of water sector.

Energy supply is one of the primary drivers of socio-economic development, and worldwide energy demand and consumption continue to rise due to increase in population, economic growth, and higher living standards. Energy generation is largely dependent on fossil fuels comprising of coal, natural gas and petroleum, which have tremendous carbon footprint, among other environmental disruptions, adversely affecting the ecosystem, and community health. Fossil fuels contributed as a fuel source for at least 80% of the U.S. energy consumption for over a century, and accounted for 81.5 % of the total U.S. energy consumption for 2015 (USEIA, 2016a). In 2013, USA was ranked as the second highest producer of fossil fuel related carbon emissions after China in the amounts of 1.28 trillion kg carbon (Boden et al. 2013).

Water and energy resources are dependent on each other for their life-cycle processes related to production and use. Decisions made for resource utilization in one sector affects the other sector, which may carry both short and long-term significant and multidimensional effects.

1.2 Water-Energy Nexus

Nexus between water and energy is important, and its comprehensive understanding is essential for the three-tier goal of achieving sustainability of resources, economic viability and reduction of environmental adversaries (Hussey & Pittock, 2012). Water is required for energy generation, and energy is required for various processes related to the water life cycle. Security and sustainability of both water and energy are inextricably linked with each other (Hussey & Pittock, 2012; Olsson, 2015, Zhang & Vesselinov, 2016; Fang & Chen, 2017).

Water is a necessity for various processes related to energy production and conversion which includes resource extraction, transportation, processing and refining of fuels, at the power plant for electricity generation as well as for transmission and distribution (Olsson, 2015; Meldrum et al. 2013; Macknick et al. 2012; Hussey & Pittock, 2012; Harto et al. 2010; Fthenakis & Kim, 2010). In 2010, 45% of the total water withdrawals in the U.S. were related to thermoelectric power sector, which also accounted for 38% of the total freshwater withdrawals (Maupin et al. 2010).

Energy is required to extract, transport, treat, store, deliver, utilize and dispose of water (Hamiche et al. 2016; Plappally & Lienhard, 2012; USEPA, 2016a). Water treatment requires tremendous expenditures of energy during water extraction from lakes and rivers; as well as during water conveyance over long-distances to remote cities. After hauling the water to treatment plants, energy is consumed to treat and then to distribute the water. After the supplied water is used, wastewater is generated through residential, commercial and industrial activities. The generated wastewater is collected and treated at wastewater treatment plants for protection of public health and avoiding the spread of disease, which requires further expenditure of energy. The treated wastewater is reused, or dispersed in nature. Globally, about 8% the total energy generation is related to water pumping, treatment and distribution (UNO, 2014b).

Land is also a resource, which is finite and shrinking. Land area development is inextricably linked with energy as well as water supply. Similarly, development of water and energy infrastructure requires land area (Cheng & Hammond, 2017; Fthenakis & Kim, 2009; van Vuuren et al. 2017). Cheng & Hammond (2017) determined land requirements for various electricity generation sources (coal, natural gas, solar, wind nuclear, hydroelectric), and found offshore wind energy to have the least energy density (GWh generation per land area utilized), while the nuclear energy to have the highest energy density. Changing climate may lead to land degradation.

The nexus approach involves understanding the interdependencies and linkages between water and energy at multiple spatial and temporal scales; finding solutions in an integrated manner to assist in decision making about resource utilization and development; and to ensure resource sustainability. Various studies have analyzed the nexus between water and energy (Bryan et al. 2016; Bukhary et al. 2018; Bukhary et al. 2016; Chen et al. 2018; Howells et al. 2013). Bryan et al. (2016) explored the water-energy-land nexus for Australia and evaluated policy implications for the year 2050 for different scenarios. Bukhary et al. (2018) analyzed the solar energy-water nexus for utility-scale solar installations in the southwestern U.S. based on the renewable portfolio standards. Chen et al. (2018) made quantitative assessments of land area utilized for cultivation (39%) and associated water withdrawal (29%) within the context of global supply chain. Howells et al. (2013) evaluated the effects of climate change on water-energy-land nexus by developing a model for integrated resource management and policy analysis.

Several current issues warrant the need to understand the nexus between water and energy. Water and energy demands are affected by growing population, urbanization, industrialization, food and energy security policies and higher living standards. One of the environmental impacts of the nexus is greenhouse emission, which contributes to environmental pollution and degradation of community health. Climate change may affect weather patterns related to temperature and precipitation causing extreme conditions of droughts and floods. For the southwest, policies regarding water rights add an important dimension to water-energy nexus, especially in the context of limited water availability.

The southwestern U.S. is the driest region in United States (Garfin et al. 2014). Climate fluctuations, along with increasing population and changing water needs, have placed an increased demand on existing water resources. Recurring drought conditions in the region augment this problem (MacDonald, 2010). Various studies predict a warmer and dryer climate, as well as longer and more intense droughts for the southwestern United States (Cayan et al. 2016; MacDonald, 2010; Jardine et al. 2013). With persistent drought conditions prevalent in the region, limited water availability has the potential to constrain the operation of power plants and other energy production activities such as solar power development in the water-limited areas. For the southwest, policies regarding water rights add an important dimension to water energy nexus, especially in the context of limited water availability.

Use of renewables, particularly, solar energy is one of the approaches that can be utilized to achieve sustainability and security of resources, economic viability and reduction of environmental adversaries. The central aim of this study was to evaluate the water-energy nexus of the southwestern United States and develop approaches for solar development and water treatment.

1.3 Solar as an Energy Resource

Solar energy is gaining popularity as a clean source of energy production globally as well as in the United States. Sunlight is an abundant resource especially in the southwest U.S. and application of this technology on an industrial scale will not only help towards energy independence, but will lead to the reduction in greenhouse gas (GHG) emissions. Solar energy has great potential as an alternate source of energy for various life cycle water related processes including water and wastewater treatment plants (Alghoul et al. 2016, Carvalho et al. 2013, Chae and Kang 2013, Garg & Joshi 2015, Schäfer et al. 2014, Shawky et al. 2015, Soshinskaya et al. 2014).Many countries are turning towards clean energy technologies. Target goals are being set and incorporated into the national energy policies to develop clean energy technologies (Aslani and Wong, 2014; Dyson et al. 2014; Munoz et al. 2017; Sahu, 2015; Yang et al. 2015; Yuan et al. 2014). 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 additional benefits, including reduction in the carbon footprint, increased job opportunities, provision of energy independence at remote locations, and an enhanced quality of life (Hernandez et al. 2014). Solar energy is vital to human life, and has been harnessed by humankind for thousands of years.

Global resource potential of solar energy is huge and far surpasses the entire global energy demand (Deng et al. 2015). Fthenakis et al. (2009) conducted a techno-economical and geographically-based analysis of the potential of using PV and CSP technologies in the U.S., and determined that by the year 2050, solar energy can potentially meet 35% of the total U.S. energy demand (electricity and fuel) and 69% of the total U.S. electricity demand. Fthenakis et al. (2009) further concluded that by the year 2100, solar energy could potentially supply 90% of the total U.S. energy needs, and along with other renewable energy sources, 100% of the total energy needs of the U.S., and hence contributing to 92% decline in carbon emission levels when compared to the carbon levels in 2005.

Typically, solar technology can be categorized as either photovoltaic (PV) or concentrated solar power (CSP). Solar PV technology generates electricity by converting sunlight directly into electricity by utilizing the photoelectric effect and the photovoltaic effect. CSP technology generates electricity indirectly by using mirrors/lenses to concentrate sunlight onto a smaller area/receiver in order to assist in heating a working fluid. Thus, solar thermal energy is changed into heat energy to drive a heat engine or generator unit using electrical power. CSP technology may broadly be classified as a dish stirling, a linear Fresnel, a parabolic trough, and a power tower. A dish stirling is a parabolic mirrored dish that concentrates sunlight onto a centrally located receiver. Linear Fresnel reflectors are long flat mirrors instead of troughs, mounted on a two-axis tracking mechanism; they are arranged in parallel arrays and angled to direct the sunlight onto a longitudinal receiver. The parabolic trough is designed using optical principles, and heats a fluid by directing solar radiation from the mirrored troughs onto a longitudinal receiver. The operation of a solar power tower requires work by directing sunlight from heliostats, which are flat movable mirrors located towards the receiver at the top of a central tower.

1.4 Research Objective and Questions

Availability of water is essential for energy generation. Any new energy development project, including solar development depends upon the availability of water. Further, various water-related processes including energy-intensive water treatment depend upon the supply of energy. The main objective of the current research was to study the water-energy nexus of the Southwestern U.S. and develop approaches for solar development and water treatment by dividing the work into two main research tasks. The research questions that were answered in this study and their corresponding hypotheses are as follows.

Research Task 1: Water for Solar Development in the Southwest

The study analyzed water requirements and availabilities for utility-scale solar development in six southwestern states of the U.S, to meet the target goals of their renewable portfolio standards from 2015 to 2030, and answered the following questions.

Research Questions

1) What are the water and land use requirements for the development of different PV and CSP technologies in the southwestern US?
2) How do the water, and land demands for various PV and CSP systems compare against the water and land availabilities for utility-scale solar development in the nineteen solar energy zones of the six southwestern states, based on renewable portfolio standards and goals of the states?
3) How the findings help understand the nexus between energy and water for successful implementation of solar technology in the region?
4) What is the associated reduction in carbon emissions due to solar development for the six states?

Research Hypothesis

- Sufficient water resources may not be available within the solar energy zones of the southwest to support utility-scale solar development. The southwest is abundant in solar resources, but persistent drought conditions, along with increasing population, have placed an increased demand on existing water resources in the region. Solar energy zones are mostly remote locations, and limited availability of water may be a hindrance to solar power development.

- Development of solar power will lead to reduction in carbon emissions. The primary energy sources in the southwest are dominantly the fossil fuels with high carbon emission rates. Solar facilities have negligible carbon emissions during their operational life, and using solar as a source of energy generation has great potential to reduce carbon emissions.

Research Task 2: Solar Energy for Treatment of Drinking Water

This study deals with understanding the water-energy nexus of three small, medium and large existing drinking water treatment plants (DWTPs) located in the southwestern United States. To offset the energy consumption of the DWTPs in a sustainable manner, distributed solar was analyzed and following questions were answered.

Research Questions

1) What are the energy consumption estimates for unit processes of the three drinking water treatment plants?
2) What is the techno-economic feasibility of using solar PV to offset the energy consumption of the three DWTPs with the long-term goal of energy independence and sustainability?
3) How do the land use demands of the solar PV compare against the existing land holdings of the DWTPs?
4) What is the quantitative reduction of the adverse environmental impacts of the nexus in terms of carbon emissions due to the development of solar system?

Research Hypothesis

- Water treatment facilities located in areas of high solar intensity, can achieve sustainability by incorporating solar into their energy source portfolio. Few studies have explored the incorporation of solar energy for water treatment plants. Moreover, the southwestern US possesses tremendous solar resources and would be a prime candidate for such implementation.
- Solar-based design results in negligible carbon emissions when compared to the non-solar based design. Energy source portfolio of the southwest primarily consists of fossil fuel based energy sources with high carbon emission rates. Using solar to offset the energy consumption has the potential to reduce the carbon footprint of the treatment plants.

1.5 Roadmap for the Study

The research work is documented in six chapters. The current chapter 1 introduces the study topics and outlines the research objectives and questions. Two major research tasks were accomplished in this study, and the details regarding the introduction, data sources, methodology, results, and conclusion for the two research topics are presented in manuscript style in chapters 2-5. Chapter 2 addressed the first research objective related to analyzing water demands and availability for solar development in the southwest and is titled "Analyzing land and water requirements for solar development in the Southwestern United States." Chapters 3-5 addressed the second research objective related to analyzing solar PV for offsetting energy consumption of three DWTPs located in the southwest. Chapter 3 is titled "Incorporating solar to offset the energy consumption of a 10 MGD drinking water treatment plant", Chapter 4 is titled "Incorporating solar to offset the energy consumption of a 90 MGD drinking water treatment plant" and Chapter 5 is titled" Incorporating solar to offset the energy consumption of a 300 MGD drinking water treatment plant". At first, the three DWTPs were designed and energy consumption was determined for unit processes involved. Next solar energy was used to meet the energy requirements of the DWTP, based on existing land-holdings of the plant and the economic feasibility of the solar system, in a standalone mode as well as in a grid-connected mode, among other analyzed scenarios. The last chapter 6 titled "Contributions and Recommendations" provides overall summary, contributions and recommendations for the tasks accomplished.

CHAPTER 2: ANALYZING WATER AND LAND REQUIREMENTS FOR SOLAR DEVELOPMENT IN THE SOUTHWESTERN UNITED STATES

This chapter deals with meeting objective one of this research. This analysis consists of determining water and land requirements and availabilities for utility-scale solar development in six southwestern states of the U.S, to meet the target goals of their renewable portfolio standards between the years of 2015-2030.

2.1 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, 13% by using renewable energy sources; and overall 0.65% of the electricity production was achieved by using solar energy (USEIA, 2016b).

Globally and nationally, fossil fuels dominate as a fuel source for energy production. However, fossil fuels are exhaustible finite resources, and various studies have predicted their depletion (Shafiee and Topal, 2009; Pearce and Turner, 1990). Fossil fuels are also expensive environmentally and economically. Usage of traditional fossil fuel sources have led to an increased carbon footprint, among other environmental disruptions. The links among GHG emissions, the consequent pollution, and the changing climate may potentially lead to an increase in climate extremes around the globe (IPCC, 2014). Various studies connect the changing climate to intensified droughts and elevated temperatures (MacDougall and Friedlingstein, 2015; Trenberth et al. 2013), wildfires, a rise in sea levels, floods, and storms. Coupled with a growing population, the changing climate may result in socioeconomic effects and issues regarding water availability (IPCC, 2014; Chen et al. 2018; Kalra et al., 2017; Thakali et al., 2016). Further, oscillating prices of fossil fuels (Aslani and Wong, 2014; Gormus et al. 2015), rising pollution levels (Atilgan and Azapagic, 2015; Hoel and Kverndokk, 1996; Withagen, 1994), and political compromises (Torres-Sibille et al. 2009) are some of the factors that have resulted in an increase in the attractiveness of clean-energy technologies. In particular, since clean-energy technology represents reduced GHG emissions and other waste products during the various life cycle processes (Arent et al. 2014; Hernandez et al. 2014; Li, et al. 2012; Pilli-Sihvola et al. 2010; Tsoutsos et al. 2005; Turney and Fthenakis, 2011).

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. 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 the associated reduction in carbon emissions. This study used a simulation model for the analysis.

Typically, solar technology can be categorized as either 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 (Polman et al. 2016).

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 (Michalena & Hills, 2013); 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 (Maupin et al. 2014). 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 Meldrum et al. (2013) based on the literature review of over 2000 publications. Harmonized values of water use for solar facilities were generated by Meldrum et al. (2013) 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 Meldrum et al. (2013) and Macknick et al. (2012) 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 solar system due to dust accumulation. The water requirement for washing ranges from 0.08 m^3 MWh^{-1} to 0.15 m^3 MWh^{-1} (Bracken et al. 2015). 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) (Sarvar et al. 2013; Mani & Pillai, 2010).

In arid desert-like regions, dust is predominantly inorganic and windborne, that adhere to the solar panel/mirror's glass exterior due to electrostatic forces of attraction and dry winds. Soil erodibility and wind erosivity are two main inextricably sources of dust generation (Gillette, 1981). Weekly cleanings are required in such dry climatic conditions. Soiling of panels/mirrors is found to be greatest in North Africa and Middle Eastern regions (Ghazi et al. 2014).

Costa et al. (2014) conducted a literature review of various studies regarding impact of dust accumulation of solar facilities between the years 2012-2015. The study reported that for a 1.5 year soiling study for PV(C-Si) in Mesa, AZ showed 74.6gm m^{-2} accumulation of dust resulting in very high efficiency losses. Costa et al. (2014) further reports another 3-month cold weather study in Mesa, AZ that resulted in 2% and 1 % efficiency losses for tilt angles of 0° and 33° respectively.

Saidan et al. (2016) 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%). Maghami et al. (2016) 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. Gillette et al. (1980) conducted field testing for determination of threshold velocity that will cause dust generation for various desert soils of Mohave Desert including playas (over 100 cm sec^{-1} for disturbed soils and over 150 cm sec^{-1} for undisturbed soils) and alluvial fans (40 to 70 cm sec^{-1} for disturbed soils and above 200 cm sec^{-1} for undisturbed soils). This dust is carried by wind and may accumulate on the surface of solar panels/mirrors, which require washing for maintenance of system's efficiency.

CSP technology has additional water requirements for cooling processes. Cooling methods can be categorized as wet, dry, and hybrid (Bracken et al. 2015). 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 the most popular. A cooling tower removes heat through evaporation. However, wet cooling encompasses the highest water usage, in the range of 3.1-3.4 m^3 MWh^{-1} (Meldrum et al. 2013). Water usage of a hybrid-cooled system is approximately 60%-80% lower than that of a wet-cooled system, and is in the range of 0.6-1.3 m^3 MWh^{-1} (Meldrum et al. 2013). Among the three, dry cooling is relatively costly and a less efficient method but encompasses the lowest water usage in the range of 0.1-0.3 m^3 MWh^{-1}. Water usage for dry cooling is approximately 77%-85% lesser than for a hybrid-cooled system (Meldrum et al. 2013). 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} (Meldrum et al. 2013, Ali, 2017, Ali & Kumar, 2017). Water usage of a hybrid-cooled system, in the range of 0.6-1.3 m^3 MWh^{-1}, is approximately 60%-80% lower than that of a wet-cooled system (Meldrum et al. 2013, Ali, 2017, Ali & Kumar, 2017). 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} (Meldrum et al. 2013, Ali, 2017, Ali & Kumar, 2017).

The southwestern U.S. is abundant in solar resources and favorable for solar development, but development of solar power in the region might be curtailed due to the limited availability of water. The southwestern U.S. is the driest region in United States (Garfin et al. 2014). Climate fluctuations, along with increasing population and changing water needs, have placed an increased demand on existing water resources. Drought conditions prevalent in the region augment this problem (MacDonald, 2010). 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.

New development necessities new water use, which could be made available from five sources of water (Bukhary et al. 2016; Klise et al. 2013) namely unappropriated surface water (USW), unappropriated groundwater (UGW), appropriated surface water/ groundwater (AW), municipal waste water (WW), and 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 1,500-10,000 mg l^{-1}, in addition to well drilling, costs are incurred for freshwater generation using reverse osmosis process (Tidwell et al. 2014b). 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 (Shrestha et al. 2011). 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 (Morales and Busch, 2010). Land usage increases as tilt angles increase (Denholm and Margolis, 2008). 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 also is higher. A single-axis 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 (Denholm and Margolis, 2008; Ong et al. 2013).

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 Ong et al. (2013). Since solar development requires a large amount of land, land might be utilized that otherwise would be used for food production. Denholm & Margolis, (2008) 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. Turney & Fthenakis, (2011) 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 (Hernandez et al. 2014). Apart from aesthetic effects (Torres-Sibille et al. 2009), the development of solar power represents ecological effects as well, particularly regarding wildlife and habitats (Tsoutsos et al. 2005). Desert environment, which is characterized by an abundance of year-round solar irradiance, solar technology 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 kW h^{-1} (Turney and Fthenakis, 2011). Therefore, using desert lands for utility-scale solar plants offer additional gains. One-third of the earth's land surface is covered with deserts (Griangers, 2013; Prabhakara and Dalu, 1976). If 4% of the deserts are utilized for solar energy production, the generated power will be able to meet the world's energy demands (Kurokawa, 2014). For solar technologies, (Burkhardt et al. 2012) reported carbon emissions for CSP trough and CSP tower as 26 and 38 g CO2eq kWh^{-1}, respectively. Hsu et al. (2012) provided emissions for PV (C-Si) as 45 g CO2eq kWh^{-1}. Kim et al. (2012) estimated emissions for PV thin-film amorphous silicon and PV thin-film cadmium telluride as 21 and 14 g CO2eq kWh^{-1}, respectively.

Solar technology has come a long way since its inception due to the technology advancements resulting in efficient and cost effective PV and CSP systems. Ongoing research for PV systems is focusing on different areas that include discovering higher efficiency solar cell materials, as well as for minimizing efficiency losses for existing PV technologies, that can be manufactured cost-effectively on a commercial scale. Innovations have been made in the field of CSP technology that uses solar thermal energy to generate electricity, by using improved materials and design methodologies for heat collection, heat conversions, power production and thermal energy storage systems (Baharoon et al., 2015; Zhang et al., 2013; Tian and Zhao, 2013; Barlev et al., 2011).

An up-to-date database of efficiency improvements in the field of solar PV have been reported by NREL, (2016) and Green et al, (2015). Hot temperatures coupled with heat losses result in greater efficiency losses in solar cells (Kalogirou, 2013a). Recombination losses in solar cells can be reduced by using quantum coherence (Scully, 2010). Not all the photons in the sunlight are absorbed by the solar cell because of the spectral mismatch. That unabsorbed photon energy is dissipated as heat in a process called thermalization (Liu, 2016; Tjong, 2013; Beeby and White, 2010). The most common thermalization efficiency loss in the solar cells leads to greater than 50% of the efficiency losses in solar cells (Alharbi and Kais, 2015), and can be reduced by using devices that allows carrier multiplication, hot carrier transport, spectrum manipulation, split-spectrum system or the use of optical concentration with thermo-photovoltaics. Solar PV is a promising technology and to make it into a competitive option for large-scale electricity generation may depend upon the commercialization of lab-tested, high efficiency solar modules (Bazilian et al. 2013; Castellanos et al. 2017; Kammen, & Sunter, 2016).

Overall, efficiency of CSP systems depend on heat collection and heat conversion processes. Solar-to-thermal efficiency relies on the performance of receivers and reflectors (López-Herraiz et al., 2017; Rovira et al., 2016; Barlev et al., 2011). It can be improved by employing heat-transfer fluids that can operate at higher temperatures (Lenert and Want, 2012), and using material and equipment that can support high operating temperatures to minimize thermal losses (Prieto et al., 2016). Employing same fluid for the processes of heat-transfer as well as thermal storage, or using design methodologies that eliminates the requirement of using heat exchangers for heat transfer, will lead to reduced thermal losses, greater efficiencies as well as reduced costs (Ma et al. 2015; Glatzmaier, 2011). Typical solar-to-electric efficiencies range between 15-20%. Continued research and efforts in the field of solar technology will lead to further improvements and more efficient and cost effective solar systems in the future (Schmalensee, 2015; Bosetti et al., 2012; Barlev et al., 2011).

Simulation modeling may play an instrumental role in the progress of solar power. System dynamics (SD) is an approach developed by Forrester (2007, 2003, 1987, 1960,1958) that is used by researchers to analyze the dynamic behavior of systems in various fields, including planning for traditional and renewable energy (Aslani et al. 2014; Bustamante and Gaustad, 2014; Dale and Benson, 2013; Houari et al. 2014; Jeon and Shin, 2014; Leopold, 2016, Mazhari et al. 2011; Moumouni et al. 2014), sustainability (Paz et al. 2013); analyzing social behavior (Simonovic and Ahmad, 2005), evaluating such environmental changes as GHG emissions (Hsu, 2012; Feng et al. 2013; Loonen et al. 2013; Robalino-López et al. 2014; Shrestha et al. 2011; Shrestha et al. 2012), cost analysis (Aslani and Wong, 2014; Hsu, 2012; Shih and Tseng, 2014), water quality analysis (Amoueyan et al. 2017; Rusuli et al. 2015; Venkatesan et al. 2011a; Venkatesan et al. 2011b), and policy-based environmental management, like water resources management (Ahmad, 2016; Ahmad & Prashar, 2010; Ahmad and Simonovic, 2006; Ahmad and Simonovic, 2000; Chen et al. 2017; Dawadi & Ahmad, 2012; Dawadi & Ahmad, 2013; Mirchi et al. 2012; Qaiser et al. 2011; Qaiser et al. 2013; Prashar & Ahmad, 2010; Tamaddun et al. 2018, Wu et al. 2013; Zhang et al. 2016), and energy management (Ansari and Seifi,, 2012; Chi et al. 2009; Dyner et al.1995; Naill, 1992). Aslani and Wong (2014) 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. Houari et al. (2014) 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 (Houari et al. 2014).

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 development 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.

2.2 Study Area

To promote solar technology, the U.S. Bureau of Land Management (BLM) initiated the Western Solar Plan in 2012 (BLM Solar, 2014). 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 (Solar PEIS, 2012).

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 1,207 km^2 in area, were recognized by the Western Solar Plan (Figure 2.1). 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 development. In 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 (BLM Solar, 2014; Bracken et al. 2015; Solar PEIS, 2012).

Summarized description of the 19 SEZs is shown in Table 2.1, while a detailed description is provided in Appendix A-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 Appendix A-1 is reflective of development areas only (Solar PEIS, 2012).

Utility-scale solar necessitates relatively flat land for cost effective development; locations with gentle slopes of less than 5% were selected as SEZs (BLM Solar, 2014). 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 Figure 2.1, 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 2.1, which reviews and summarizes information provided by BLM's Solar Plan (2014) and the Final Solar Energy Development Programmatic Environmental Impact Statement (Solar PEIS, 2012). County populations were obtained from (U.S. Census Bureau, 2016). 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 2.1). 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 (Solar PEIS, 2012). Dust samples of the southwest U.S. show the largest particle diameters to be between 0.02-0.1 mm (Gillette, 1980). Some of the SEZs are areas of dry lake beds or playas (Table 2.1). Such areas contain fine-grained soils infused with salts, and hence may produce saline/alkaline dust (Reheis, 1997). Other SEZs are alluvial flats that are also contributors of dust (Table 2.1). This dust is carried by wind and may accumulate on the surface of solar panels/mirrors, requiring washing to maintain system efficiency.

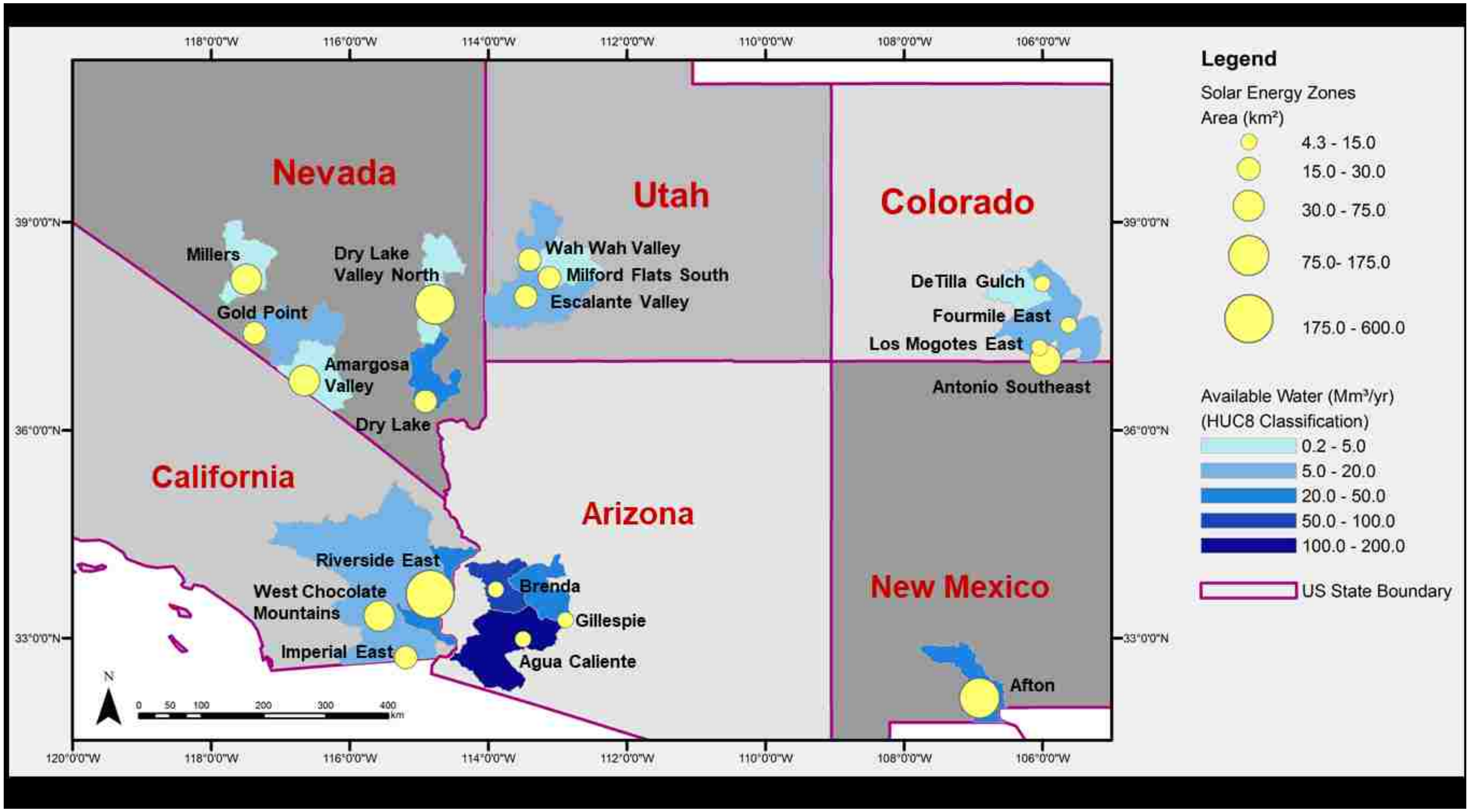


Figure 2.1: Map of the six states of the southwestern U.S., showing the 19 solar-energy zones and the corresponding 8-digit HUC regions.

Table 2.1: Details about the 19 Solar-Energy Zones in AZ, CA, CO, NM, NV, and UT.

S. N.	SEZ	State	SEZ County / 2015 Population	HUC-8 Region/ State	SEZ Location	Water Availability (Million m^3 year^{-1})			
						UGW	AW	BGW	WW
1.	Agua Caliente	AZ	Yuma/ 204,275	15070201	Lies in the Palomas Plain, surrounded by the Palomas and Baragan Mountain. Sparsely populated surrounding area.	0.00	22.04	139.25	0.60
2.	Brenda		La Paz/ 20,152	15030105	Lies within the Ranegras Plain, surrounded by the Bouse and Bear Hills, Plomosa, Granite Wash and Harquahala Mountains.	0.00	6.39	50.57	0.00
3.	Gillespie		Maricopa/ 4.167,947	15070104	Surrounded by the Gila Bend Mountains and Centennial Wash.	0.00	6.61	29.51	0.00
4.	Imperial East	CA	Imperial/ 180,191	18100204	Located in the Sonoran Desert and within the jurisdiction of the California Desert Conservation Area (CDCA) in East Mesa.	0.00	1.97	12.70	0.00
5.	Riverside East		Riverside/ 2,361,026	18100100 15030104	Located within the Mojave Desert. Consists of flat barren plains with sandy portions. Areas surrounding the SEZ are developed.	0.00	23.60	14.08	2.58
6.	West Chocolate Mountains		Imperial/ 180,191	18100204	Located in Colorado Desert. Gently sloping topography towards the Salton Sea.	0.00	1.97	12.70	0.00
7.	Antonito Southeast	CO	Conejos/ 8,130	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.	0.00	7.36	0.00	0.00
8.	De Tilla Gulch		Saguache/ 6,251	13010004	Located in the northwest part of San Luis Valley. SEZ terrain is gently sloping. Some development exists in surrounding areas.	0.00	3.62	0.00	0.00
9.	Fournile East		Alamosa/ 16,496	13010003	Lies in the eastern San Luis Valley, on a flat alluvial fan in the high-elevation San Luis Basin.	0.00	4.04	1.38	0.00
10.	Los Mogotes East		Conejos/ 8,130	13010002	Located in the southwestern San Luis Valley, on a flat alluvial fan in San Luis Basin.	0.00	7.36	0.00	0.00
11.	Afton	NM	Dona Ana / 214,295	13030102	Lies in the West Mesa of Mesilla Basin.	0.00	2.78	34.54	7.37
12.	Amargosa Valley	NV	Nye/ 42,477	18090202	Lies in the Amargosa Desert, which is bounded by the Funeral Mountains and Yucca Mountain.	0.02	0.27	0.00	0.00
13.	Dry Lake		Clark / 2,114,801	15010012	Lies in Dry Lake Valley, surrounded by the Arrow Canyon Range to the west and Dry Lake Range to the southeast.	28.34	0.21	1.38	0.00
14.	Dry Lake Valley North		Lincoln/ 5,036	16060009	Lies within Dry Lake Valley, and is bounded by ranges including the North Pahroc, Black Canyon, Burnt Springs, and West Range.	0.42	0.51	0.00	0.00
15.	Gold Point		Esmeralda/ 829	16060013	Lies within Lida Valley.	5.13	0.26	0.00	0.00
16.	Millers			16060003	Situated in Big Smoky Valley.	3.32	0.16	0.00	0.76
17.	Escalante Valley	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.	0.00	3.32	2.94	0.31
18.	Milford Flats South		Beaver/ 6,354	16030007	Situated in the northeastern part of Escalante Desert.	0.00	1.36	0.00	1.66
19.	Wah Wah Valley			16030009	Situated in Wah Wah Valley, bounded by Shauntie Hills, Wah Wah and San Francisco Mountains	3.59	2.69	1.38	0.00

2.3 Data Sources

2.3.1 Renewable portfolio standards

The RPS of the six states (AZ, CA, CO, NM, NV, and UT) are shown in Table 2.2, and are based on information provided by the Database of State Incentives for Renewables & Efficiency (DSIRE, 2016). Under the RPS, adoption of renewables would lead to the provision of federal incentives and tax rebates (DSIRE, 2016). The states may have incorporated specific standards and goals related to solar development 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 2.2). AZ, CO, and NM have incorporated DR targets within the RPS requirements; however, DR carve-outs were not incorporated within the simulation model and thus not the scope of this work. In the current study, it was assumed that RPS based solar power development was solely utility-scale. In terms of 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 2.2: 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% from solar by 2015 and 6% from 2016-2025 i.e., 1.5 % of total retail sales
UT	20% by 2025	-

4.2.2 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 Tidwell et al., (2014a) (Figure 2.2). 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 (Tidwell et al. 2014a). The water data was translated into eight-digit Hydrologic Unit Codes (HUCs) by utilizing the method of aggregation /averaging. Furthermore, Tidwell et al. (2014a) 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 development in the 19 SEZs.

4.2.3 Water usage

Within the framework of simulation model in this study, water consumption and withdrawal for PV and CSP systems was computed based on the work of Meldrum e. al., (2013) 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. *Water withdrawal* is either water usage by diversion from a source or water removal from the ground. In contrast, *water consumption* is the water usage by permanent removal from source, and thus is unavailable for reuse.

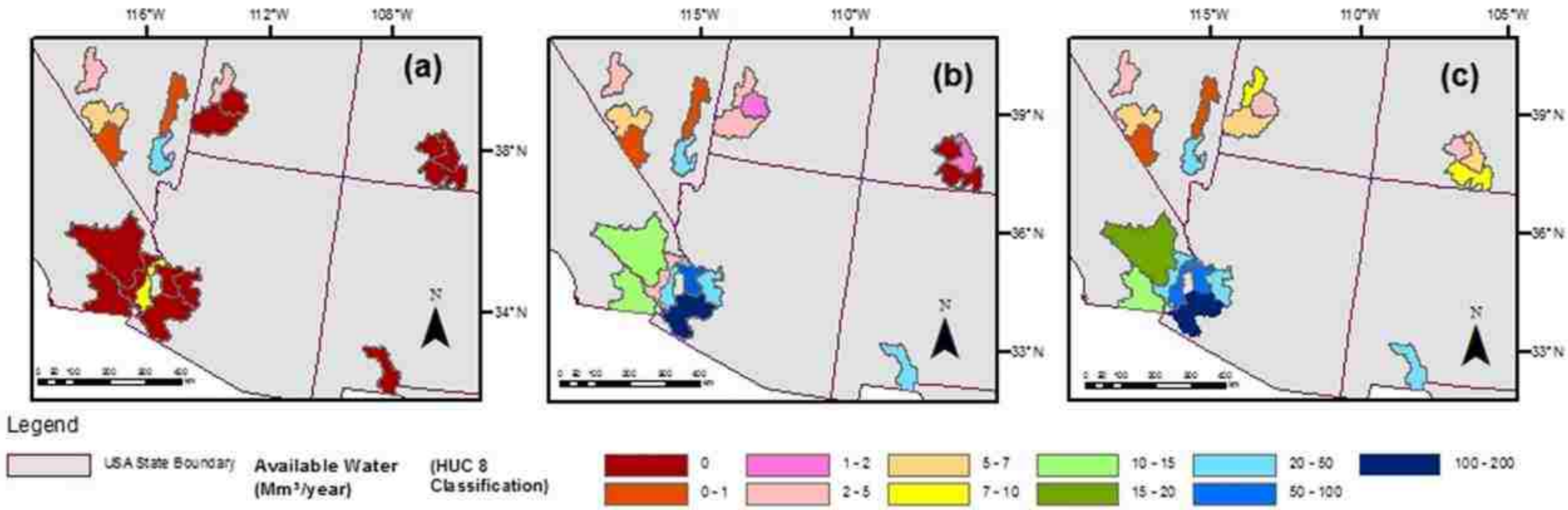


Figure 2.2: Water availability for the 19 solar-energy zones for six states in the southwest U.S. for three scenarios. (a) Scenario 1: Unappropriated available water is the summation of unappropriated groundwater and unappropriated surface water resources; (b) Scenario 2: Available water is the summation of brackish groundwater, unappropriated groundwater, unappropriated surface water, and wastewater; (c) Scenario 3: Available water is the summation of appropriated water, brackish groundwater, unappropriated groundwater, unappropriated surface water, and wastewater. Water availability estimates were extracted from Tidwell et al. (2014a).

4.2.4 Land availability

Data regarding the land area available within the SEZ was extracted from BLM Solar (2014) and Solar PEIS (2012), as shown in Table 2.1.

For the development of utility-scale solar technology, 19 SEZs totaling over 1,207 km^2 in area were located in Arizona (AZ), California (CA), Colorado (CO), Nevada (NV), New Mexico (NM), and Utah (UT) (Figure 2.1, Table 2.1). As shown by Table 2.1, three SEZs are located in AZ, CA and UT; four are located in CO; five are in NV; and one is located in NM having area coverage of 34.82 km^2, 665.2 km^2, 75.5 km^2, 66.1 km^2, 244.3 km^2 and 121.2 km^2 respectively. As can be seen, largest allocation of land is for SEZs of California.

4.2.5 Land usage

Land usage was computed for utility-scale solar plants, based on the work of Horner and Clark (2013). 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 Horner and Clark (2013) 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.

4.2.6 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 LBL (2016) 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 (USEIA, 2016c) in order to determine electricity generation at utility-scale solar installations (Wong, 2011).

4.2.7 Carbon emissions

Estimations of carbon emissions were made using median values for carbon emissions obtained from Moomaw et al., (2011) (Table 2.3) and the 2014 energy-source distribution of electricity generation (USEIA, 2016d) for the six southwestern states (Table 2.4). Energy-source distribution was assumed to stay constant between 2015 and 2030, due to lack of data.

Table 2.3: 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 2.4: 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

2.4 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?

2.4.1 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 Meldrum et al. (2013), 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 Meldrum et al. (2013), 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 Horner & Clark, (2013) as discussed in Section 2.3.5. Horner & Clark, (2013) 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^{-1}), 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 (Ong et al. 2013).

2.4.2 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 (Meldrum et al. 2013, Hsu et al. 2012, Asdrubali et al. 2015):

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

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

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 (Khan& Arsalan, 2016). For harmonization, module efficiency of 19.3% was used, as the mean of the module efficiencies reported by (Polman et al. 2016), 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 (Meldrum et al. 2013, Hsu et al. 2012, Khalid et al. 2016).

Typically, design lifetime of solar technologies is 30 years (Meldrum et al. 2013, Hsu et al. 2012). 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 (Hsu et al. 2012, Kim et al 2012).

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.

2.4.3 Simulation Modelling

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) (Blair et al. 2014) to analyze system performance and energy costs for grid-connected renewable-energy power projects. The Solar Deployment System (SolarDS) model, developed by NREL (Denholm et al. 2009), 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 (Richmond et al 2012). 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.

2.4.4 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 (Figure 2.2):

- 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 (Tidwell et al. 2014a), 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.

2.4.5 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 2.3) and the energy-source distribution of electricity generation for six southwestern states (Table 2.4). 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.

2.5 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.

2.5.1 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 Table 2.5-2.6. 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 (Table 2.5-2.6).

Water withdrawal estimates were reported by very few of the selected publications. Other than constructions estimates, water withdrawal was assumed 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 (Sinha et al. 2012, Skone et al. 2012). Water use during the construction phase can be reduced by employing techniques that reduce earth movement for site preparation (Sinha et al. 2012). 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 2.5 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.

Table 2.5: 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

Table 2.6: 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

Monocrystalline silicone, multicrystalline silicone, and cadmium telluride are mature photovoltaic materials that are typically used for utility-scale solar plants (Polman et al. 2016), 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 2.5.

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 less than 0.5 gal MWh^{-1} for both PV and CSP technologies (Table 2.5). 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 (Horner & Clark, 2013). The harmonized estimates for land-use intensity are shown in Table 2.6. 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 (Ong et al. 2013). 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 2.7). 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 Figure 2.3 and Figure 2.4. 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 (Frisvold & Marquez, 2013; Averyt et al. 2013). Comparisons were also drawn between total land use estimates generated by the simulation model and the land-use estimates reported by (Ong et al. 2013, Frisvold & Marquez, 2013). As shown in Table 2.8, the model estimates are in good agreement with the results of these studies.

Table 2.7: 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})	Frisvold, & Marquez, (2013) Operational Water use ($x10^3 m^3 yr^{-1}$)	Macknick et al. (2012) Operational Water use ($x10^3 m^3 yr^{-1}$)	This Study Operational Water use ($x10^3 m^3 yr^{-1}$)	Frisvold & Marquez, (2013) Land Use ($x10^6 m^2$)	Ong et al. (2013) Land Use ($x10^6 m^2$)	This Study Land Use ($x10^6 m^2$)
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

Table2.8: Variability in Performance Parameters Reported in Literature

Solar Technology	Parameters	Parameters			
		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

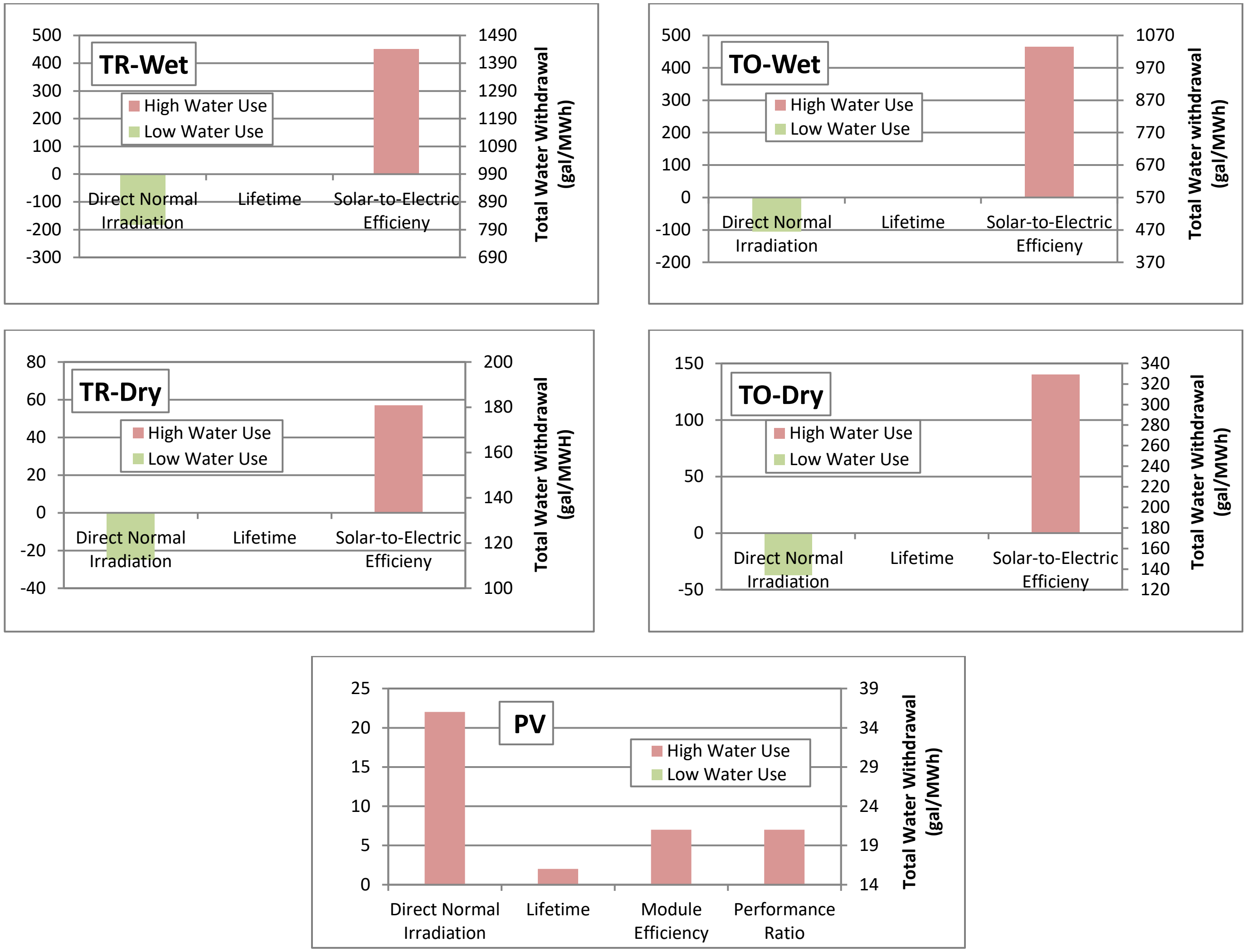


Figure 2.3: Sensitivity analysis to represent the variation of median water use estimates for solar photovoltaic (PV), Tower wet-cooling (TO-Wet), Tower dry-cooling (TO-Dry), Trough wet-cooling (TR-Wet), and Trough dry-cooling (TR-Dry), across a range of performance parameters.

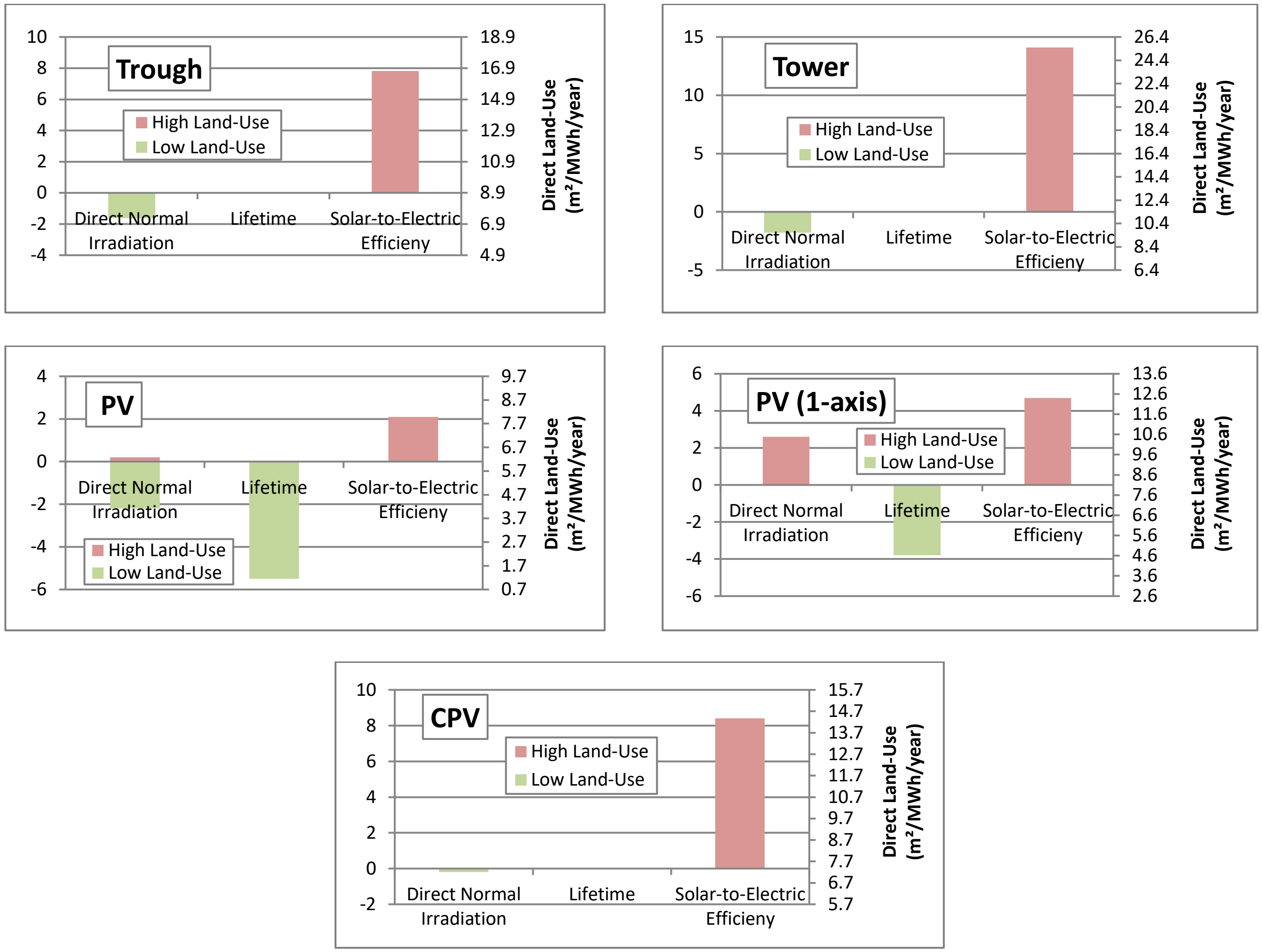


Figure 2.4: Sensitivity analysis to represent the variation of median land use estimates for solar photovoltaic (PV), concentrated photovoltaic (CPV), power tower and parabolic trough, across a range of performance parameters.

2.5.2 Simulation Modelling

Total water and land-use estimates generated for various configurations of PV and CSP technologies in Section 2.5.1 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 (Figure 2.5-2.10). 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 2.5). Total water use estimates for PV and CPV were found to be 14 and 19 gal MWh^{-1} (Table 2.5). Direct land use was 1.4 times smaller than total land use (Ong et al. 2013).Comparisons with the available land were drawn against the total land requirements of solar installations.

2.5.2.1 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.

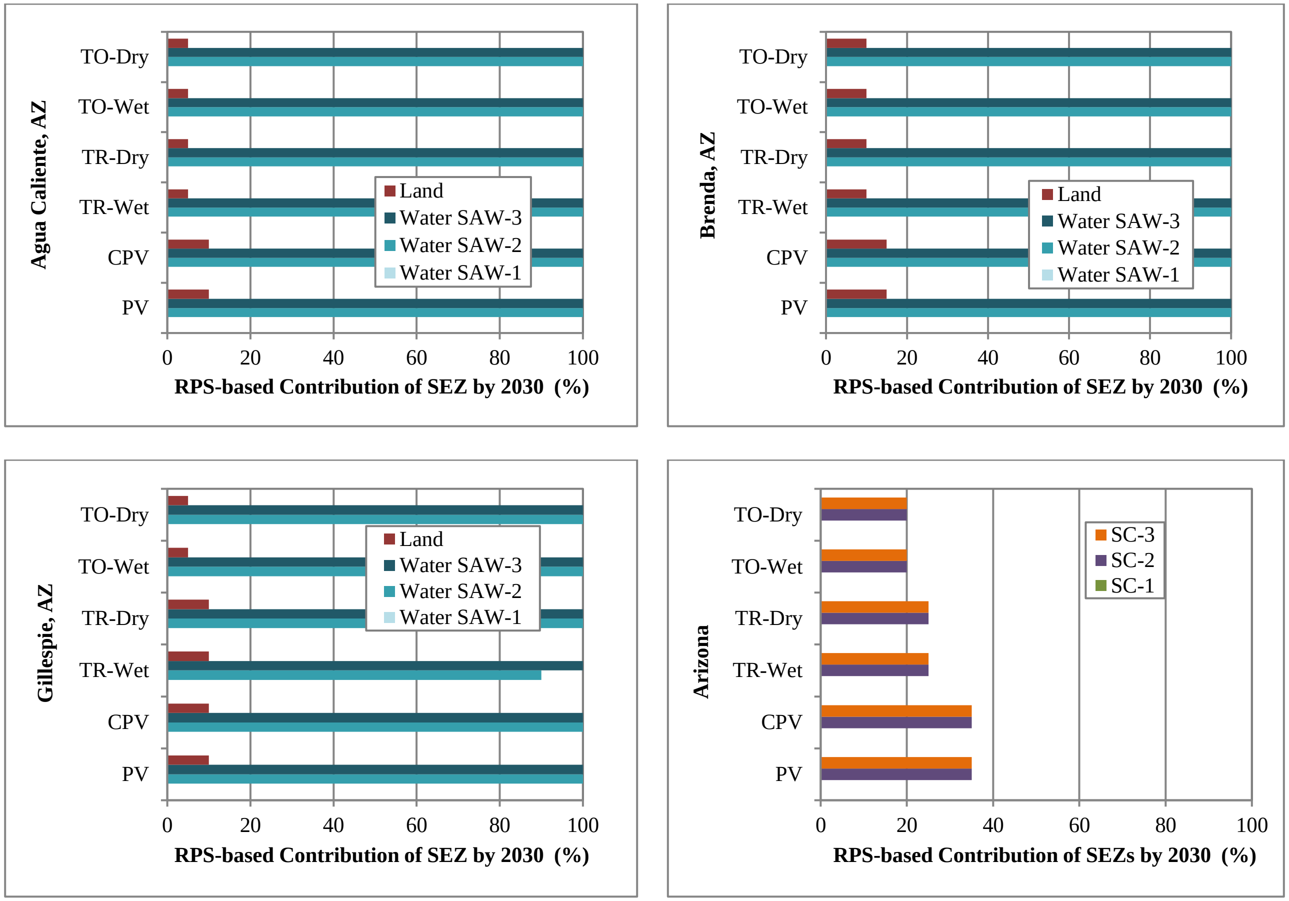


Figure 2.5: Contribution of Arizona and its solar energy zones (Agua Caliente, Brenda and Gillespie) to fulfill renewable portfolio standards of the state for various solar technologies of solar photovoltaic (PV), Tower wet-cooling (TO-Wet), Tower dry-cooling (TO-Dry), Trough wet-cooling (TR-Wet), and Trough dry-cooling (TR-Dry).

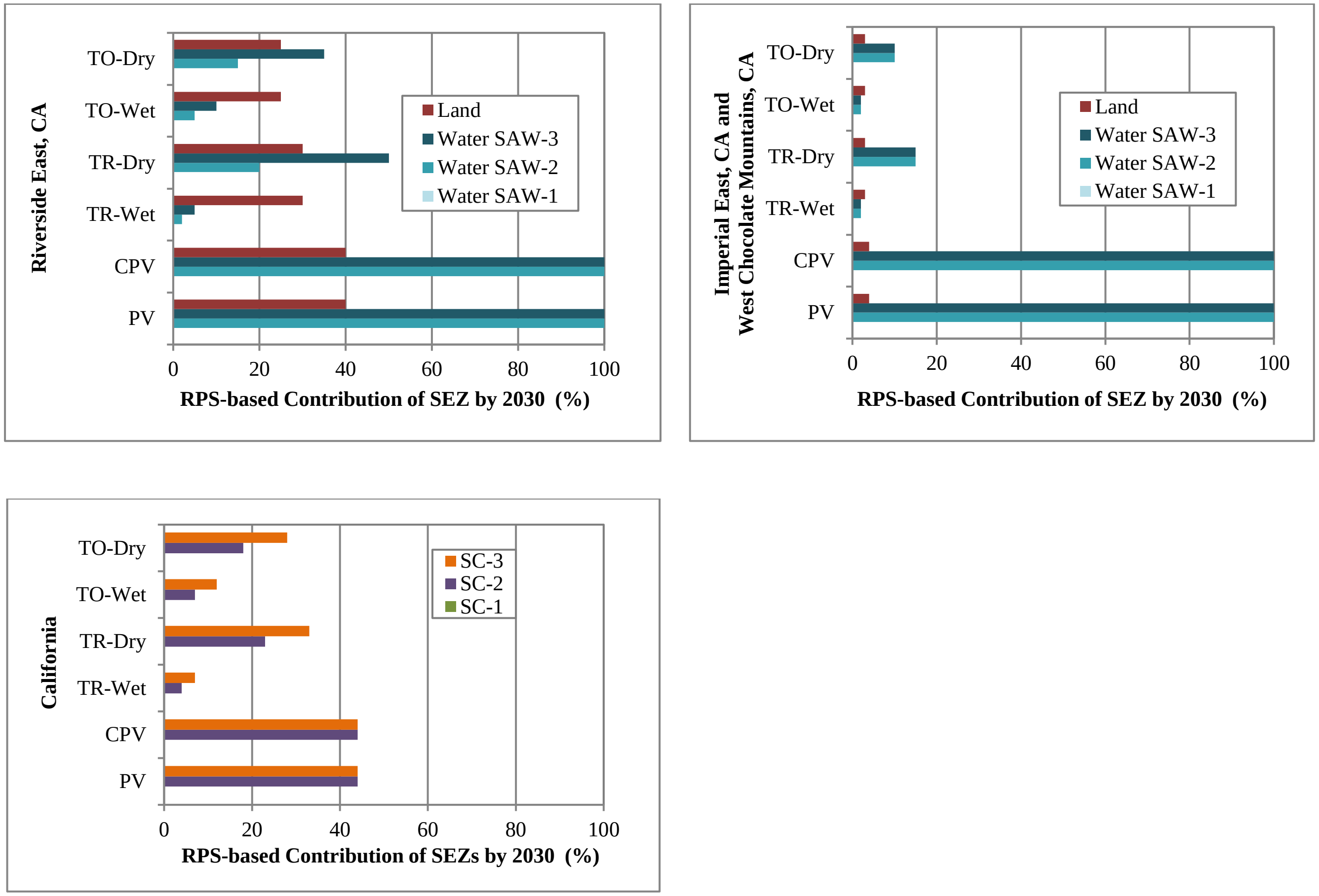


Figure 2.6: Contribution of California and its solar energy zones (Riverside East, Imperial East, West Chocolate Mountains) to fulfill renewable portfolio standards of the state for various solar technologies of solar photovoltaic (PV), Tower wet-cooling (TO-Wet), Tower dry-cooling (TO-Dry), Trough wet-cooling (TR-Wet), and Trough dry-cooling (TR-Dry).

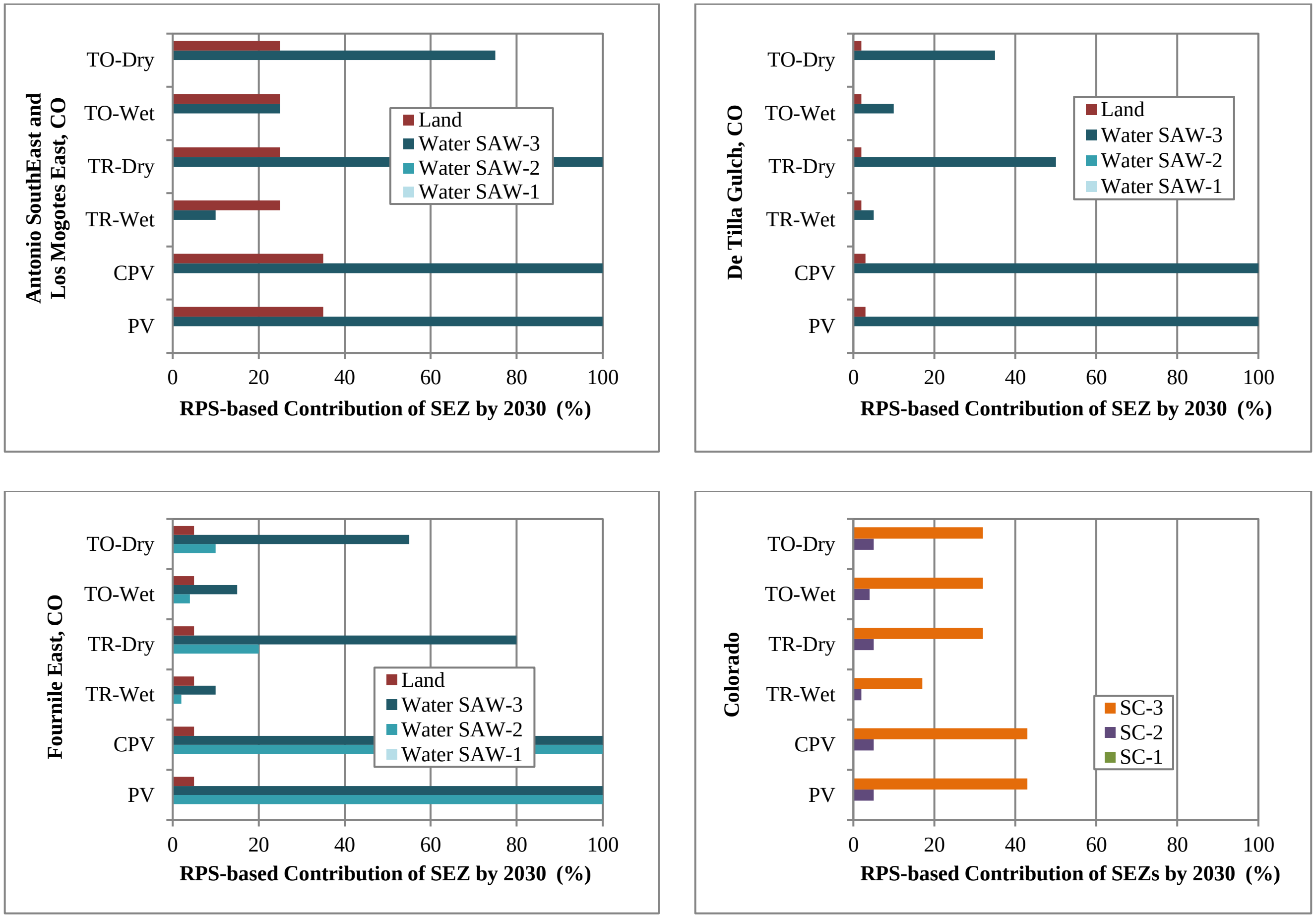


Figure 2.7: Contribution of Colorado and its solar energy zones (Antonio Southeast, Los Mogotes East, De Tilla Gulch, Fournile East) to fulfill renewable portfolio standards of the state for various solar technologies of solar photovoltaic (PV), Tower wet-cooling (TO-Wet), Tower dry-cooling (TO-Dry), Trough wet-cooling (TR-Wet), and Trough dry-cooling (TR-Dry).

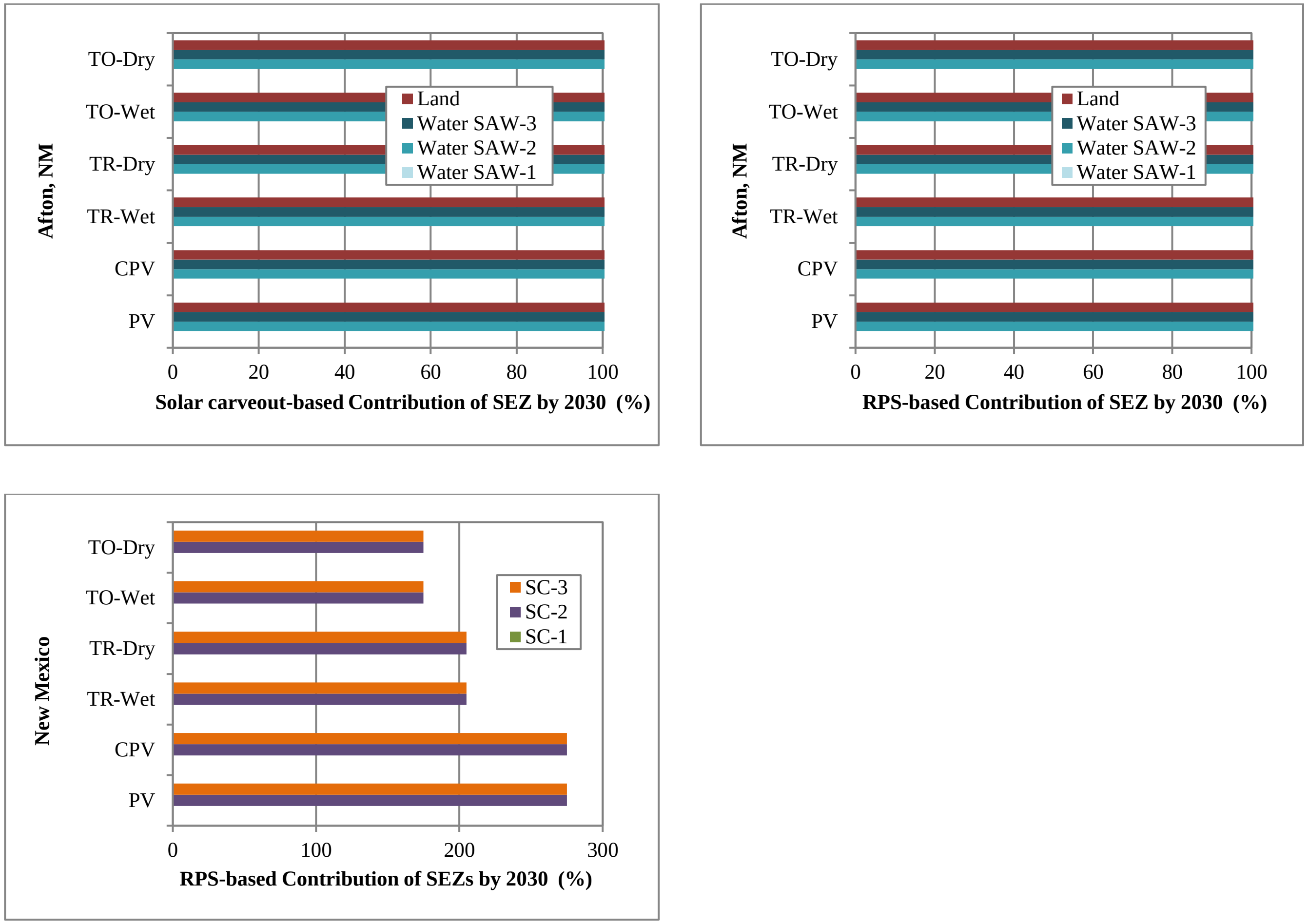


Figure 2.8: Contribution of New Mexico and its solar energy zone (Afton) to fulfill renewable portfolio standards of the state for various solar technologies of solar photovoltaic (PV), Tower wet-cooling (TO-Wet), Tower dry-cooling (TO-Dry), Trough wet-cooling (TR-Wet), and Trough dry-cooling (TR-Dry).

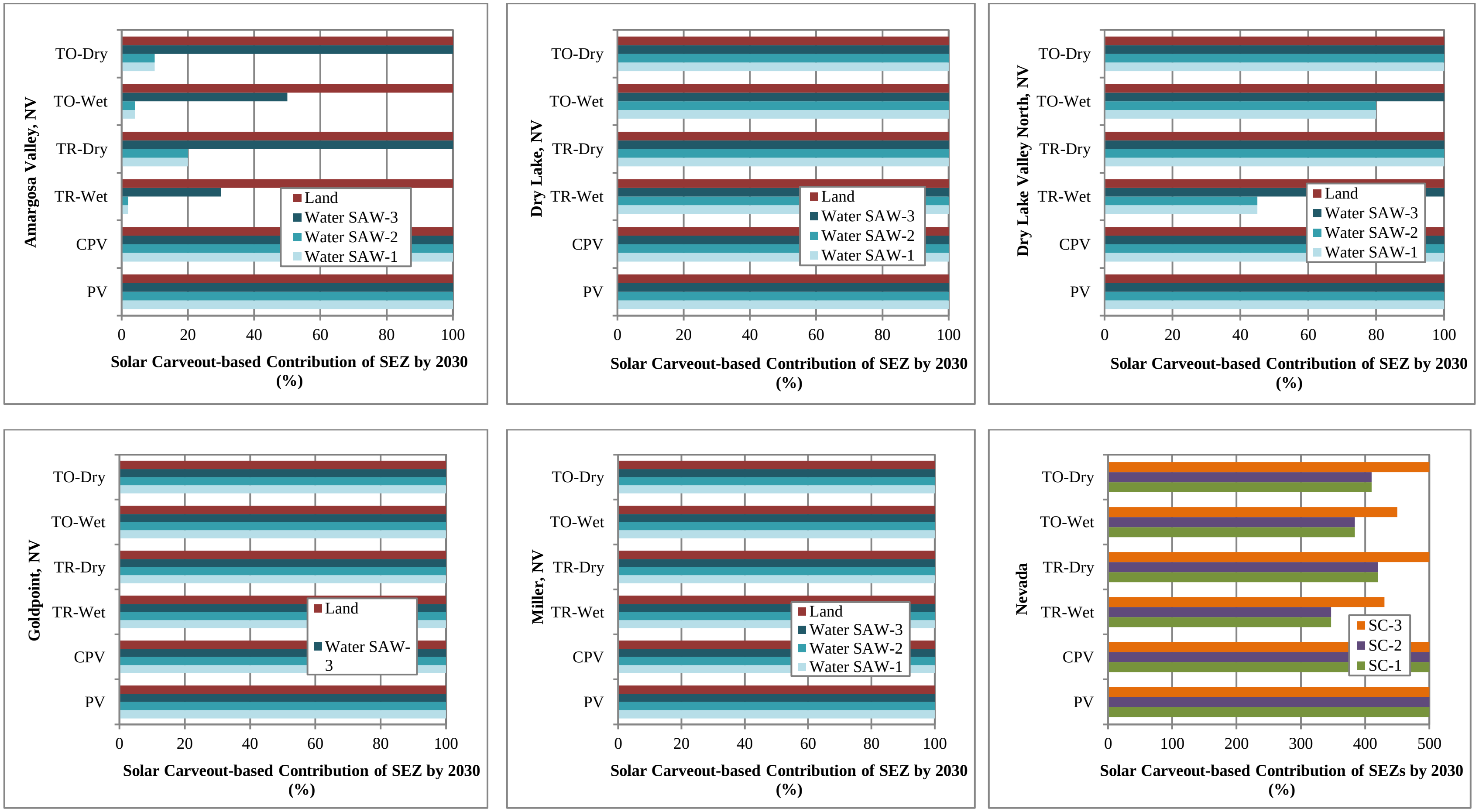


Figure 2.9a: Contribution of Nevada and its solar energy zones (Amargosa Valley, Dry Lake, Dry Lake Valley North, Goldpoint, Miller) to fulfill renewable portfolio standards of the state for various solar technologies of solar photovoltaic (PV), Tower wet-cooling (TO-Wet), Tower dry-cooling (TO-Dry), Trough wet-cooling (TR-Wet), and Trough dry-cooling (TR-Dry).

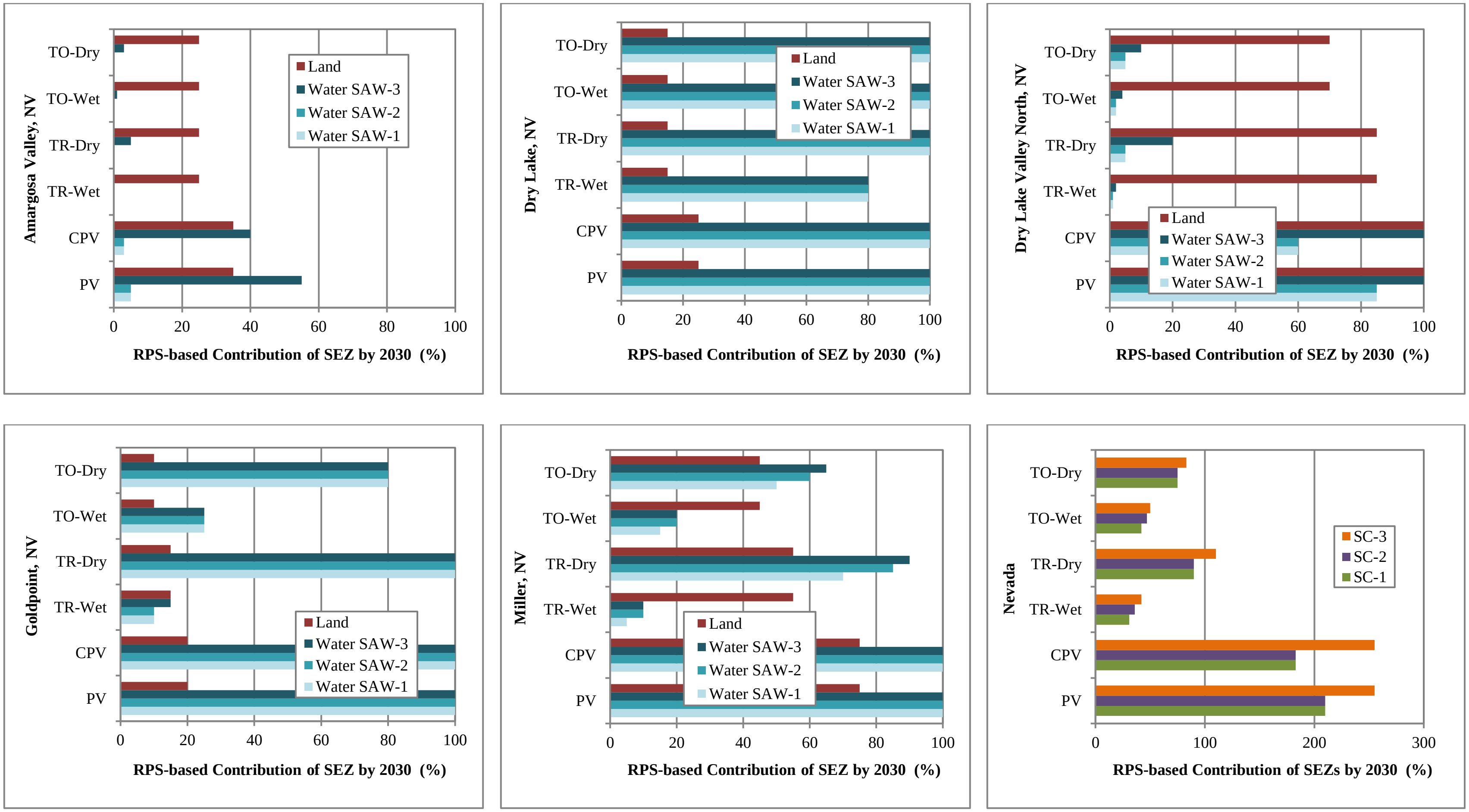


Figure 2.10b: Contribution of Nevada and its solar energy zones (Amargosa Valley, Dry Lake, Dry Lake Valley North, Goldpoint, Miller) to fulfill renewable portfolio standards of the state for various solar technologies of solar photovoltaic (PV), Tower wet-cooling (TO-Wet), Tower dry-cooling (TO-Dry), Trough wet-cooling (TR-Wet), and Trough dry-cooling (TR-Dry).

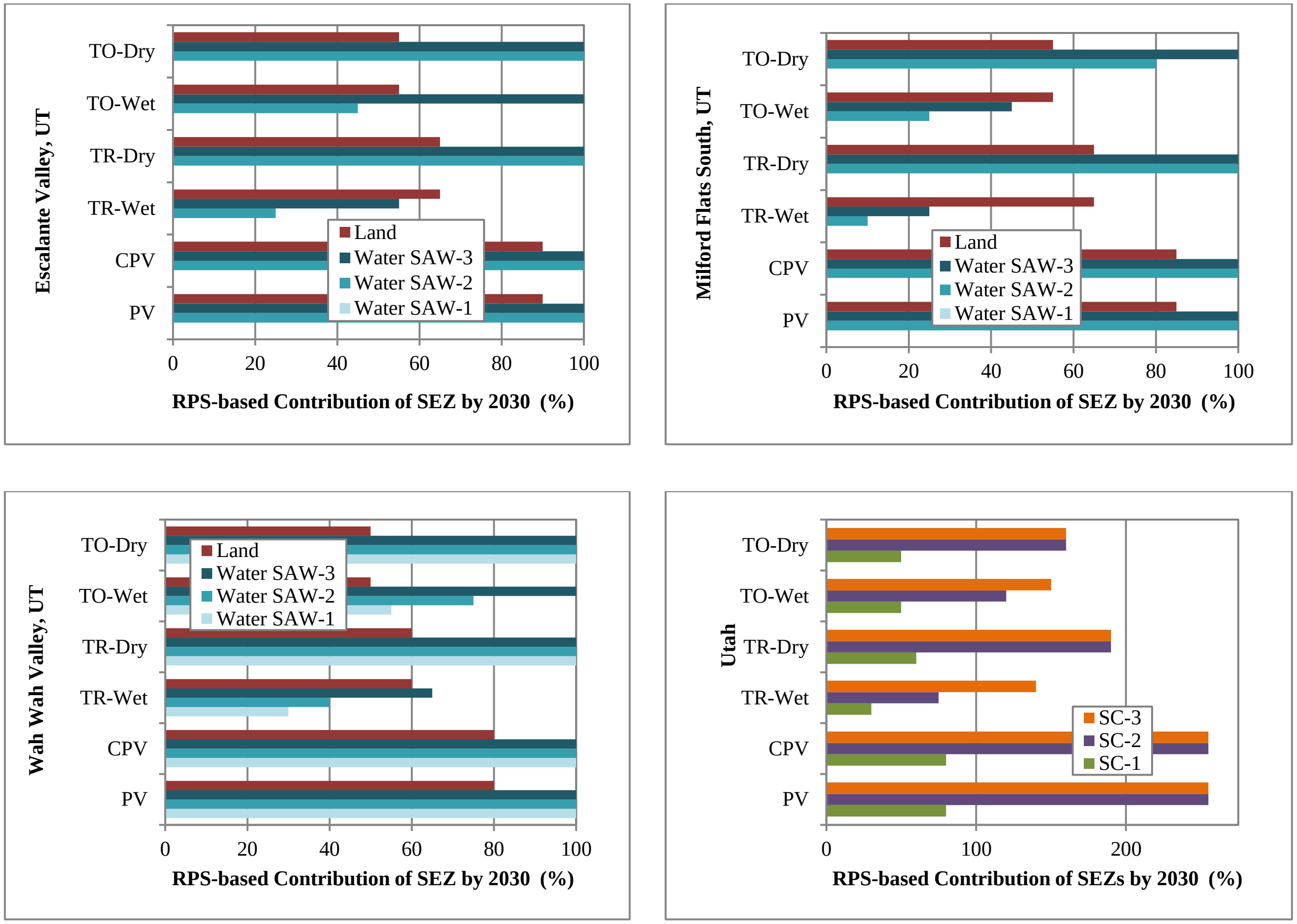


Figure 2.11: Contribution of Utah and its solar energy zones (Escalante Valley, Milford Flats South, Wah Wah Valley) to fulfill renewable portfolio standards of the state for various solar technologies of solar photovoltaic (PV), Tower wet-cooling (TO-Wet), Tower dry-cooling (TO-Dry), Trough wet-cooling (TR-Wet), and Trough dry-cooling (TR-Dry).

Arizona did not contain any UGW or USW resources within their three SEZs (Table 2.1, Figure 2.2, Figure 2.5). 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 development (Table 2.2). 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 2.1, Figure 2.2). Making use of this resource warrants desalination and would incur additional construction and operational costs since desalination is an energy intensive process (Shrestha et al. 2011). 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 Figure 2.5. 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 Figure 2.5. 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 (Figure 2.5)

For California, 50% of their electricity production must be achieved by using renewable energy by 2030 (Table 2.2); 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 (Tidwell et al. 2014a), 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 (Figure 2.7). BGW (1.38 million m^3 yr^{-1}) was available only for SEZ Fournile East (Figure 2.2), whereas AW availability was 15.02 million m^3 yr^{-1} (Tidwell et al. 2014a) 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 (Figure 2.8). 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 (Figure 2.8). 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} (Figure 2.2), 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 (Figure 2.9a and Figure 2.9b). Overall, PV systems could potentially fulfill over 200% of RPS-based requirements, when considering all 5 SEZs. Compared to other technologies, overall, development 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 (Figure 2.10). As shown by Figure 2.10, 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 development of water-intensive CSP technologies (Bracken et al. 2015, Averyt et al. 2013, Macknick et al. 2012b). 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 and raises questions about suitability of these areas as SEZs. 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 development 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 (Klise et al. 2013), but the option may not always be available. Water can also be transported to the site, but again, this demands additional costs (Tidwell et al. 2014b)

Solar Energy Environmental Mapper (Solarmapper, 2016) 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 (Cook et al. 2004). Gleeson et al. (2010) 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 (Weiss et al. 2009, Mulroy, 2017), as well as longer and more intense droughts (Trenberth et al. 2014). Water demands are expected to increase under the changing climate and growing population in the southwest (Seager et al. 2007). 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 (Figure 2.2). 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 (Kenney & Wilkinson, 2011). Various policies have been established to support solar PV and CSP (Timilsina et al. 2012, Wiser et al. 2011), 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. Macknick & Cohen, (2015) 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 31721 MW of capacity in the six southwestern states by 2030, Bracken et al. (2015) 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 Wiser et al. (2016), 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. Murphy et al. (2014) 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. Nonhebel, (2005) analyzed land usage of PV and biomass for energy production and determined PV to have better potential for energy generation. Arent et al. (2014) 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}. (Denholm & Margolis, 2008) 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 (Denholm & Margolis, 2008). Fthenakis & Kim, (2009) 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). Capellán-Pérez et al. (2017) 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%. Waite, (2017) analyzed 10% of contaminated or degraded land areas in the U.S. for development 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 (Bukhary et al. 2017a; Bukhary et al. 2017b; Green & Bremner, 2017; Sampaio & González, 2017; Zhang et al. 2017). 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 (Baharoon et al. 2015, Zhang et al. 2013, Tian & Zhao, 2013, Barlev et al. 2011). Continued research will lead to further improvements and more efficient and cost effective solar systems in the future (Barlev et al. 2011, Schmalensee, 2015, Bosetti et al. 2012). Improvements in efficiency will result in reduced usage of water and land for solar development.

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 Figure 2.5-2.10, 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.

2.5.2.2 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 2.5.2.1).

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 $kgC0_2eq$, 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 U.S. Environmental Protection Agency (EPA) (USEPA, 2017). 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 $kgC0_2eq$ 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 development 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 (NYSERDA, 2016). The RPS for New York State stipulates that 29% of their electricity consumption should be met by using renewables by 2015 (DSIRE, 2016). Sekar & Sohngen, (2014) 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.

Greenblatt, (2015) 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 191.4-387.4 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. Wiser et al. (2016) 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. Mai et al. (2014) determined a 69-82% reduction in carbon emissions if 80% of electricity is generated using renewable energy by the year 2050 for United States.

2.6 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 development , 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 development, 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 to 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 development 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 development 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.

CHAPTER 3: INCORPORATING SOLAR TO OFFSET THE ENERGY CONSUMPTION OF A 10 MGD DRINKING WATER TREATMENT PLANT

This chapter deals with meeting objective two of this research. The research task is accomplished by first understanding the water-energy nexus of the small 10 MGD plant, determining the energy consumption of the various unit processes used for treatment of drinking water, and then offsetting the energy consumption in a sustainable manner by using solar PV based on existing land-holdings of the plant and economic feasibility of the PV system. Reduction in carbon emissions due to solar development was also estimated.

3.1 Introduction

As fossil fuel resources are depleting, solar energy, particularly through photovoltaic conversion, is a promising way to meet the world's future energy demands. Solar as an infinite source of energy, does not directly introduce polluting emissions into the environment (Fahrenbruch & Bube, 2012). Solar energy helps reduce the dependence on fossil fuel-based energy sources as well as environmental pollution including GHG emissions caused by fossil fuel use (Foley & Olabi, 2017; Lin & Ahmad, 2017; Schandl et al. 2016; Gill et al. 2017; Zoundi, 2017). Recently, there has been increased emphasis on including sustainability into the water infrastructure design. One of the ways to achieve sustainability goals is to incorporate renewables into the operation of water and wastewater treatment plants to offset their energy consumption achieving both economic and environmental betterment. In this study, techno-economic assessment of using solar PV was conducted for a small drinking water treatment plant.

Water treatment is an integral component of modern life, and vital for safeguarding the health of any community. Globally, water-related operations utilize about 1-2 % of total energy consumption. In the U.S., there are about 60,000 small and large drinking water systems and about 15,000 wastewater treatment facilities, and consume about 3-4% of the overall energy consumption (Spellman, 2013). Energy consumption of drinking water and wastewater treatment plants corresponds to about 56-75 billion kWh year^{-1} (Goldstein and Smith, 2002, Sanders & Webber 2012) and about $4 billion annually (Spellman, 2013). Drinking and wastewater facilities account for up to 35 % of a municipal government's energy budget (Pirnie and Yonkin, 2008). For large wastewater treatment plants (WWTP), about 15-30% of the operation and maintenance costs are related to energy consumption (WEF, 2009); whereas for small WWTP, costs related to energy consumption constitute about 30-40% of the total operation and maintenance cost (WEF, 2009). Reduction of carbon emissions and reduced energy costs may be the motivating factors for incorporating PV into the design of existing water infrastructure.

Energy consumption has been evaluated in drinking water and wastewater treatment plants by various studies (Bailey, 2012; Newell, 2012; Klein et al. 2005, Molinos-Senante & Sala-Garrido, 2017). Studies have also identified the effect of plant size on energy consumption and determined that larger WWTPs consume less kWh of energy per unit volume of water treated than smaller plants (WEF, 2009). Bailey, (2012) and Newell, (2012) determined energy consumption and the associated carbon emissions for water reuse plants and wastewater treatment plants, respectively. Wen et al. (2014) reported that the city of Qingdao, China, utilized about 1% of the total energy consumption for drinking water treatment, whereas utilization was 4-5% for the distribution of drinking water and treatment of the generated wastewater.

Various factors warrant using solar PV for achieving the sustainability goals of water treatment systems. Changing climate coupled with growing population places increased demands on water treatment facilities. Between the years 1950-2000, the US population increased from 152.3 to 272.7 million (US Census Bureau, 2012), but the demands on water supply systems increased over three fold during this period—as determined by U.S. Environmental Protection Agency (USEPA) (USEPA, 2016a).. Thus employing alternate ways to generate energy, such as using PV or using energy conservation measures, can help in offsetting energy-related carbon emissions as well as cost reduction for these treatment facilities (USEPA, 2016a).

Solar PV provides several advantages. It can be implemented on a residential, commercial, and utility-scale. It can be installed in both urban and rural areas: ground-mounted and on rooftops (Gagnon et al. 2016; Maammeur et al. 2017; Margolis et al 2017; Mohammed et al. 2017; Omar & Mahmoud, 2017; Ntsoane, 2017; Okoye et al. 2016). Gagnon et al. (2016) determined the rooftop area suitable for the installation of solar PV in the U.S to be approximately 8130 km^2, resulting in the generation of 1.4 million GWh per year. Margolis et al. (2017) analyzed 47 cities in the U.S. and determined that Los Angeles and New York to have the largest potential for rooftop PV. Full utilization could result in annual power generations of 13.8 million MWh and 10.7 million MWh; meeting about 60% and 18% of the estimated consumption, respectively. Solar PV can also be installed as decentralized, independent systems in locations where the traditional electrical grid may not be accessible (Bhandar et al. 2017; Loizidou et al. 2015; Rashwan et al. 2017). The performance of solar PV is greatly affected by shading or cloud cover, which can be overcome by employing reliable energy storage systems for solar PV for provision of a stable supply of electricity.

However, solar energy deployment faces barriers related to land resource availability and techno-economic feasibility (Yaqoot et al. 2016). Solar energy installations require large land resources so development of solar energy may be limited due to land constraints, especially in urban areas. Proximity to military bases, airports, high population density zones, and city centers also prevent use of PV (Wadhawan & Pearce, 2017). There may also be the additional factor of competing land demands from various sectors including housing and food production (Sharmina et al. 2016). Rural areas usually have large unused land areas for deployment of solar energy. However, deployment may not be possible due to proximity to locations including conservation areas, national parks, wetlands, lakes and rivers, forests, and areas utilized by high-commercial value crops or food production (Sharmina et al. 2016 Anwarzai & Nagasaka, 2017; Cevallos-Sierra & Ramos-Martin, 2018; Solar PEIS, 2012; Yushchenko et al. 2017). Since smaller treatment plants are typically present in smaller, more remote communities—which are likely to have land available—application of solar PV has the potential to increase the sustainability of such plants.

The implementation of solar energy also depends on economic feasibility (Branker et al. 2011). Acquiring land in densely populated areas may be expensive and can affect the economic feasibility of a solar project. Financial barriers that may affect the economic feasibility of solar photovoltaics also include high capital costs, taxes, and operation and maintenance (O&M) costs (Bazilian et al. 2013; Haegermark et al. 2017; Hammad et al. 2017; Ramírez-Sagner et al. 2017; Rodrigues et al. 2016). Ramírez-Sagner et al. (2017) analyzed 314 districts in Chile and determined them to be economically feasible for residential and commercial PV installations. In many cases, it is also essential for grid-connected solar systems to be in close proximity to transmission lines and roads for the solar project to be economically feasible (Noorollahi et al. 2016).

Water and wastewater treatment facilities located in areas of high solar intensity, can achieve sustainability by incorporating solar energy into their energy source portfolio. The southwestern US possesses tremendous solar resources and would be a prime candidate for such implementation. Solar PV possesses great potential to be used as an energy source for various water and wastewater treatment facilities (Chae and Kang 2013, Garg and Joshi 2015, Ghaffour et al. 2013; Schäfer et al., 2014, Soshinskaya et al. 2014, Thomson and Infield 2002). Few studies have explored the incorporation of solar energy for water treatment plants (Bukhary et al. 2017b; Bukhary et al. 2017c, Soshinskaya et al. 2014). The overall objective of this investigation was to explore the technical feasibility of using solar photovoltaics (PV) as an energy source for a small drinking water treatment plant. Specifically, the investigation includes:

(1) The design of a water treatment plant -focusing on the energy driving unit from each unit process and the computation of energy requirements to operate the plant;
(2) Sizing the solar PV system to meet the energy demands of the plant. The energy use and solar energy system computations were based on an actual small water treatment plant, 9.7 million gallons a day (MGD), located in the southwestern region of United States, where solar intensity is highly favorable for PV generation;
(3) Evaluating land requirement for the proposed PV system and comparing it with the existing land-holdings of the plant;
(4) Evaluating the economic feasibility of using solar PV;
(5) Determining the reduction in carbon emissions compared to a non-PV based design.

The methodology used in this study can be adopted as a roadmap for incorporating renewables as a source of electricity generation for drinking water treatment plants.

3.2 Study Area

The selected 9.7 MGD DWTP provides treated water to a city, with a population of 8,606 (U.S. Census Bureau, 2010), located in the southwestern United States. The DWTP was considered a small system since it served a community of 10,000 or less under Safe Drinking Water Act (USEPA, 2016b). The semi-arid city has an average total precipitation of 126.5 mm, while the average maximum and minimum temperature are 67.6°F and 34.9°F, respectively (WRCC, 2016). The city has a total land area of 9.48 km^2 (U.S. Census Bureau, 2015).

The city is underlain by alluvial aquifers and a basalt aquifer. The main source of drinking water for the city is groundwater, which is entirely tapped from basalt aquifer. It has an approximate width of 6.44 km, a length of 24 km and an average depth of about 305 m extending about 61-183m below land surface. Water production is over the amount of 0.063 $m^3\ s^{-1}$, with an observed drawdown of 0.9 m, but the drawdown had negligible effect on the water levels of surrounding wells. The water from these wells is delivered and combined at the treatment plant. The quality of the groundwater is very good other than arsenic levels, which are around 100 ppb in the form of arsenate As (V).

3.3 Data Sources

Data used in this study consisted of raw water quality from the wells (Table 3.1), process flow diagram (Figure 3.1) of the treatment plant, and operational details that were obtained from the DWTP managers. The plant is 12 years old. Additional data to design the unit operations were obtained from Crittenden et al. (2005).

Raw water characteristics, obtained from DWTP managers, revealed the groundwater to be of high water quality except arsenic levels that were about 100 parts per billion (ppb). This value exceeded the U.S. Environmental Protection Agency's limit of 10 ppb, set as the maximum contaminant level for arsenic in public water supplies. The plant process flow diagram is shown in Figure 3.1. Since the groundwater is of high quality water (low turbidity < 5 NTU, low TOC < 4 mg l^{-1}, low color < 10 c.u), the treatment train consists of the coagulation, followed by filtration and disinfection. The treatment plant operates 24 hours per day.

The available landholdings for the DWTP were determined using ArcMap software. The landholdings were compared against the land area requirements of the solar.

The data to estimate net reduction carbon emissions were obtained from Moomaw et al., (2011). Moomaw et al. (2011) provided median estimates of carbon emission data in units of $gCO_2eq\ kWh^{-1}$ as 4 for hydroelectric energy, 12 for wind energy, 16 for nuclear energy, 18 for energy generated from biomass, 45 for geothermal energy, 46 for photovoltaics, 469 for natural gas, 840 for petroleum-based energy, 1001 for coal generated energy. The sources of electricity, also known as electricity mix or energy mix for the State was obtained from U.S. Energy Information Administration (USEIA) (USEIA, 2016d) as shown in Table 3.2.

The financial parameters used to perform the economic evaluation were based upon the review of various publication in the years 2016 and 2017 (Fu et al. 2017; DSIRE, 2017, Kang & Rohatgi, 2016; Krupa & Harvey 2017; Lai & McCulloch 2017; Mundada et al 2016; Musi et al 2017; Reiter et al 2016). The parameters are listed in Table 3.3.

Table 3.1: Water quality characteristics for the treatment plant.

Parameter	Units	Average value	USEPA MCL*/ SMCL**/ guidelines
pH	Unitless	8	6.5-8.5
Water temperature	°C	19	Not regulated
Arsenic	mg l^{-1}	100	10

*MCL: Maximum contaminant level
**SMCL: Secondary maximum contaminant level

Table 3.2: State's electricity source mix for various energy sources.

Energy Sources for Electricity Generation	State Electricity Source Mix (%)
Coal	23.51
Natural Gas	56.41
Petroleum	0.07
Bio-power	0.1
Geothermal	8.5
Hydropower	7.42
Nuclear	0
Solar	3.04
Wind	0.95

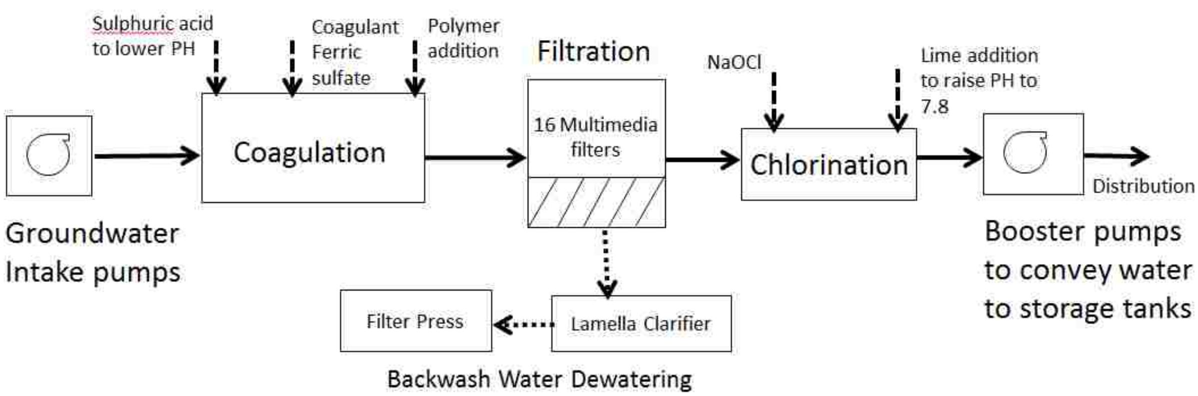


Figure 3.1: Process flow diagram for the treatment plant. Solid arrows track treatment of water, whereas dashed arrows represent the sludge generated and its treatment as well as chemical additions in the plant.

Table 3.3: Financial Parameters used for economical assessment using SAM.

	Parameter	Unit	Values
Direct Cost	Module	$ Watt^{-1}	0.87
	Inverter	$ Watt^{-1}	0.29
	Battery Bank	$ Watt^{-1}	160
	Balance of equipment cost	$ Watt^{-1}	0.29
	Installation labor	$ Watt^{-1}	0.13
	Contingency	%	4
Indirect capital Cost	Permitting, environmental studies, grid interconnection	$ Watt^{-1}	0.1
	Engineering and developer overhead	$ Watt^{-1}	0.57
O&M Cost	Fixed annual cost	$ kW^{-1} year^{-1}	$15
Project Term Debt	Debt Fraction	%	100
	Loan Term	Years	25
	Loan rate	% year^{-1}	3
Analysis Parameters	Analysis period	Years	25
	Inflation Rate	%	2.5
	Real Discount Rate	%	8
Tax and Insurance Rates	Federal income tax rate	% year^{-1}	28
	State income tax rate	% year^{-1}	0.0
	Sales tax	%	8.1
	Insurance rate	% of installed	0.25
	Salvage value	costs	20
Property Tax	Property tax rate	% year^{-1}	0.0

3.4 Methodology

Unit processes of the DWTP were designed using the data provided by the DWTP managers. Any missing design information was obtained from Crittenden et al. (2005). Components of the unit processes governing the energy usage were identified and the energy consumption was determined. The computations were made using Microsoft Excel Spreadsheet. Solar PV system was used to offset the energy consumption of the DWTP. The technical and economic assessment of the proposed PV was made using System Advisor model (SAM).

The 9.7 MGD DWTP treats groundwater obtained from seven wells, located at a distance of about 9.7 km from the treatment plant. The coagulation and filtration steps of the DWTP aim at removing arsenic using ferric sulfate as a coagulant (Figure 3.1). These processes reduce arsenic levels from 100 ppb to 10 ppb. Chlorination is used for disinfection and provides 4 log inactivation of viruses. It also leaves chlorine residual to travel through the distribution system. Booster pumps are used to pump the water to elevated storage tanks.

Energy consumption was related to pumping operation for most processes, except that of soda ash mixing system and filter press for residual management. The methodology utilized in this study is unique in the way that a thorough investigation was undertaken to determine the energy consumption of each unit process of the DWTP by utilizing the design flow rate representing the worst-case scenario for the plant. The results were validated by comparing the estimated motor sizes with the plant's motor sizes. The computed energy consumption was utilized as an input for PV design; as oppose to other studies that utilize the electric load based on the current electric bill.

The following provides details regarding the design of the DWTP units, determination of the energy consumption of the various unit processes, as well the technical and the economic assessment of utilizing solar PV to offset partially or completely the energy consumption of the DWTP.

3.4.1 Energy consumption computations

The water entered the treatment plant; the first treatment process it underwent was coagulation, which involves addition of ferric sulfate. Mixing of the coagulant with the water for formation of flocs is necessary and occurred in the conduit structure between coagulation and filtration processes. Metering pumps were used for coagulant addition, sulfuric acid for pH reduction, and polymer addition as a flocculation aid. Energy consumption associated with pumping operation was determined by using the following equation (Mays, 2005; WEF, 2009).

$$Ep = \frac{\gamma Q H t_h}{e}$$

Where Ep = Energy consumption of the pump (kWh day^{-1}),

γ = specific weight (kN m^{-3}),

Q = flow (m^3 sec^{-1}),

H = total dynamic head (m), and

t_h= motor operational hours (hours day^{-1})

e = wire-to-water efficiency.

Total dynamic head is the sum of vertical lift, pressure head and friction losses, whereas wire-to-water efficiency is the product of pump, drive and motor efficiency. The pumps operated for 24 hours per day.

Multi-media filters allow for separation of the flocs from the liquid. The criterion provided by Reynolds & Richards, (1996) was used to design the filters. Anthracite, sand and garnet made up the media composition of the multimedia-filter with effective sizes of 1.0 mm, 0.5 mm, and 0.25 mm, respectively. For anthracite, sand and garnet, layer depths of 530 mm, 230 mm and 115 mm, respectively were used. Surface wash pumps were used to break up the clogged surface layer of the filter media and were designed based on the criteria provided by Hendricks (2006). The multi-media filter was backwashed once per day. The wash water generated after backwashing flows by gravity and is stored in a tank before being pumped to a lamella clarifier for treatment. Ergun equation was used to determine clean-bed head loss (Crittenden et al. 2005) for the filters. Filters are backwashed when the head loss exceeds the available operating head (1.8-3 m), as per operation manuals provided by the plant filters are also sometimes backwashed based on a pre-defined schedule to avoid bio fouling of the filters.

Next, sodium hypochlorite is used for disinfection. Chlorination process was designed primarily using the CT design criteria specified by USEPA. CT is the product of contact time and concentration of free chlorine residual. Other literature utilized includes Lee and Lin, (2007) and Crittenden et al. (2005). Based on EPA groundwater rule, the groundwater was treated for 4-log removal of viruses. Additionally the water is chlorinated to achieve a chlorine residual in the distribution system. For effective mixing, the chlorine contact tank was equipped with baffles, based on the design criteria provided by Lee and Lin, (2007). A CT value of 12 mg l^{-1}min was used for the design of the chlorine contact basins.

After the water is chlorinated, lime slurry is added to increase the pH to 7.8. Lime is delivered in bulk form and is mixed on site. Daily lime requirements are 3.2 m^3 day^{-1}. Energy consumption due to the mixing operation was estimated based on the criteria provided by Reynolds & Richards, (1996). The energy consumption of the lime slurry addition to the finished water, using a metering pump, was determined using equation shown in Section 3.4.1.

For treatment of the backwash water generated in the filters, a lamella clarifier and filter press are used. Lamella clarifier or inclined-plate clarifier is an improvement over conventional sedimentation process, since the area requirements reduce almost 90% compared to the latter case. Inclined plates increase the effective settling area. The solids accumulate and then slide off the inclined plates under gravity. An angle of 45° was provided for the inclined plates (Liu & Liptak, 1999). Lamella clarifier was designed using the criteria provided by Hendricks (2016) and Kawamura, (2000). The energy-consuming unit for lamella clarifiers is the sludge transfer pump.

The waste sludge obtained from the operation of lamella clarifier is dewatered using belt-filter presses. It is a mechanical dewatering technique, which involves moving belts for continuous dewatering of sludge. The pressure zones can be divided as gravity drainage zone, low-pressure zone and high-pressure zone. In the gravity drainage zone, the water is removed from the sludge under gravity on a conveying belt. Within the pressure zones, the sludge is sandwiched between upper and lower belts, while contact pressure increases from low to high. The belt-filter press was designed based on the criteria provided by Force, (1998), USEPA (1987), Qasim, (1998), Shammas & Wang (2007) and Lee & Lin, (2007). The end-product is formation of sludge cake with 20-30% solids and filtrate. Energy consumption associated with belt-filters was estimated using the criteria provided by Shammas & Wang (2007).

Four booster pumps are used to transport treated water from the treatment plant to an elevated storage tank, to be further distributed throughout the city. The energy consumption associated with booster pumps was estimated using equation shown in Section 3.4.1.

3.4.2 System Advisor Model

SAM, a techno-economic modelling tool was utilized in this study for the technical and economic assessment of the solar system (Dobos et al., 2014; Gilman et al. 2008; Blair et al. 2008). This tool is open source and available for free, and can be downloaded from the National Renewable Energy Laboratory (NREL) at http://sam.nrel.gov. It can be used for residential, commercial, and utility-scale projects. Various studies have used SAM for analyzing solar technologies (Bukhary et al. 2017b, Bukhary et al. 2017c; Cameron et al. 2008; Kang et al. 2017; Jones-Albertus et al., 2016; MacAlpine et al. 2017; Mileva et al. 2016; Pierce et al. 2013; Tozzi & Jo, 2017; Wagner et al. 2017).

Tozzi & Jo, (2017) reviewed various renewable energy simulation models including the System Advisor Model. Kang et al. (2017) analyzed the financial feasibility of 86 kW commercial PV system using SAM and found it to be matching grid parity. MacAlpine et al. (2017) analyzed the effect of shading on 46 residential PV systems, and compared the on-site performance measurements with the performance estimations generated by SAM. The comparison showed the median yearly bias errors to be less than or equal to 2.5%, determining SAM to be a reliable model for shading analysis.

3.4.2.1 Technical assessment

For the technical and economic analysis, inputs to SAM include weather information of the site being analyzed, electric load data, PV system design parameters related to the panel type, inverter, and the battery. For financial assessment, inputs required are related to capital costs, incentives, tax information and various other financial assumptions. The user is responsible for the correct input of the parameters.

SAM was utilized to design the PV system. Since the DWTP plant was operated 24 hours a day, battery storage was included. Desired array size and the inverter’s DC-to-AC ratio were provided as inputs for the design of the PV system. Module and inverter type were selected from the SAM database; their parameters were used to design the number of modules and inverters and system capacity.

Battery storage was designed by providing the inputs of desired bank capacity and desired bank voltage. Based on the characteristics of the chosen battery, battery capacity, battery cells in series and strings in parallel were estimated. SAM is equipped to model vanadium redox flow, lead-acid and lithium ion batteries.

3.4.2.2 Economical assessment

For economic assessments, the main outputs of SAM were net present value (NPV), and levelized cost of energy (LCOE).

NPV provides the present value of the net cash flows of a project over its design life. Positive NPV is indicative of a profitable project, whereas negative NPV indicates a non-viable project. NPV can be estimated using the following equation:

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{I_t}{(1+r)^t} - C_O$$

Where Co=Investment costs, I_t= net cash inflows for time period t, T=Project's life term, r=discount rate

Levelized cost of electricity (LCOE) is the present value of the cost of the energy generated by the PV system over its design life. It is generally computed as cents per kWh. LCOE value is affected by the initial investment costs, state or federal incentives, depreciation method selected, O&M costs, insurance costs, property taxes, debt costs as wells as salvage value of the project. LCOE is a useful metric for making financial decisions when comparing solar PV with another renewable or with the electric utility. The LCOE can be calculated using the following equation:

$$LCOE = \frac{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{Q_t}{(1+r)^t}}$$

Where C_t= Cost for time period t, and Q_t is the energy generation in kWh in time period t. LCOE can be real or nominal based on whether it was adjusted for inflation. Real LCOE incorporates inflation within its calculation by using real discount rate in the denominator rather than nominal discount rate. Since real LCOE is adjusted for inflation, it is typically used for long-term analysis while nominal LOCE is used for short-term analysis.

3.4.3 Land requirements

The available landholdings for the DWTP were determined using ArcMap software. The landholdings were compared against the land area requirements of the solar PV estimated by SAM.

3.4.4 Carbon emissions

Direct carbon emissions for solar PV are negligible during operation of the system. However, there are some emissions during manufacturing and transportation of the panels, during construction and then disintegration of the solar facility (Nugent & Sovacool, 2014). Net reduction in carbon emissions was estimated for this study by deducting emissions generated before incorporating solar PV from emissions generated after incorporating solar PV to offset the energy consumption of the DWTP. The product of electricity source distribution (Table 3.2) and the median emission estimates data in $gCO_2eq\ kWh^{-1}$ provided by Moomaw et al. (2011) was used to estimate carbon emissions for the DWTP for the non-PV based design.

Components of the unit processes governing the energy usage were identified and energy consumption was determined, which was used as an electric load input for SAM. SAM was utilized for the technical and economic assessment of the proposed PV, to offset the energy requirements of the DWTP.

3.5 Results and Discussion

The results of this study are depicted in Figures 3.2 to 3.5 and Tables 3.4 to 3.6, and are discussed as follows:

3.5.1 Energy consumption

The water demand for the city is met by withdrawing water from seven groundwater wells. The DWTP treated groundwater obtained from seven wells, located at a distance of about 9.7 km from the treatment plant. The depths for the seven wells were 148 m (< 0.07 m^3 sec^{-1}), 159 m (< 0.07 m^3 sec^{-1}), 155 m (< 0.07 m^3 sec^{-1}), 120 m (< 0.13 m^3 sec^{-1}), 142 m (< 0.08 m^3 sec^{-1}), 142 m (< 0.08 m^3 sec^{-1}), and 142m (< 0.04 m^3 sec^{-1}). All seven wells tap into the same basalt aquifer. The water from these wells is delivered and combined at the DWTP.

At first, the groundwater undergoes coagulation at the DWTP. The addition of chemicals to the water requires metering pumps (Table 3.4). Two metering pumps were provided for each chemical addition, where one was reserved as a back-up. The flow rate for the chemicals was taken as 0.023 m^3 $hour^{-1}$, 0.18 m^3 $hour^{-1}$, and 0.001 m^3 $hour^{-1}$ for the addition of coagulant, sulfuric acid, and polymer, respectively – these flow rates were provided by the DWTP managers. Water-to-wire efficiencies used for the assessment of energy consumption of pumps are shown in Tables 3.4.

Water filtration requires 16 multi-media filters including an extra filter to incorporate redundancy. A filtration rate of 10 m $hour^{-1}$ was used. Clean bed head-loss was found to be 0.24 m. Net available operating head of 2 m was used. The filters are backwashed once per day for 15 minutes. The energy-consuming units in filtration are surface wash pumps applied for duration of 5 minutes and backwash water transfer pumps (Table 3.4). The filter-to-waste time is 15 minutes. Filtration recovery is 96%. After the filters are backwashed, the backwash water is stored in a 134 m^3 basin before being pumped to lamella clarifiers for dewatering.

After the water is filtered, it is chlorinated for residual effect and for 4-log removal of viruses, as required by USEPA groundwater rule. A 1020 m^3 contact basin provides one-hour detention time based on average flow conditions as recommended by USEPA. In the design, eight pass-around-the-end baffles were provided for adequate mixing of sodium hypochlorite with the treated water, with length-to-width ratio of 40:1 as recommended by USEPA. A residual chlorine concentration of 1.6 mg l^{-1} is provided to ensure protection against possible microbial contamination within the water distribution system. Metering pumps are used to add sodium hypochlorite to the water (Table 3.4).

Table 3.4: Energy consumption estimates of the drinking water treatment plant.

s.no.	Unit Process	Sub-Processes	Energy Driving Unit	Plant Motor Size (hp)	Estimated Motor Size (hp)	Energy Consumption (kWh day^{-1})	Energy Intensity (Wh m^{-3})	Efficiency (%)
1.	Coagulation	Coagulant addition	Metering pump	0.5	0.5	1.8	0.05	0.76
		Polymer addition	Metering pump	0.5	0.5	1.8	0.05	0.76
		Acid Addition	Metering pump	0.5	0.5	1.8	0.05	0.76
2.	Filtration		Surface wash pumps	-	4.5	5.5	0.15	0.74
			Backwash water transfer pumps	7.5	7.5	20.9	0.57	0.76
3.	Chlorination	Chlorine addition	Metering pumps	0.5	0.5	1.8	0.05	0.76
4.	Lime Addition		Lime Mixer	0.5	0.5	11.3	0.31	0.8
			Lime Feed Pump	1.5	1.3	22.8	0.62	0.76
5.	Lamella Clarifier		Polymer Pump	0.5	0.5	1.8	0.05	0.76
			Sludge transfer pumps	-	3.5	2.7	0.07	0.72
6.	Water Reclamation Basins		Water Transfer Pumps	25	25	18.7	0.51	0.76
7.	Filter Press		Filter Aid Pumps	0.25	0.2	0.94	0.03	0.76
			Filter Press & Feed Pump	6	5	21	0.57	-
8.	Booster Pumps		Pump#1	200	187	$3.33x10^3$	90.7	0.8
			Pump#2	125	123	$2.20 x10^3$	59.9	0.8

Lime addition is made to lower the water PH to 7.8 before it is pumped to elevated storage tanks using booster pumps. Lime addition system consists of mixing of lime slurry and lime metering pumps. Bulk lime is delivered to the DWTP and mixing of the lime slurry is achieved within the DWTP. Energy consumption related to lime mixing is shown in Table 3.4. A velocity gradient of 900 sec^{-1} for a detention time of 30 sec was used in the design.

Two booster pumps are provided to transport water to elevated storage tanks. Two additional pumps are provided as back-up pumps. Energy consumption for the booster pumps asshown by Table 3.4 was found to be 5.53 MWh day^{-1}.

The backwash water is treated using lamella clarifier and belt-filter presses. Two lamella clarifiers are provided. The water used for backwashing is clarified by the lamella clarifier. The plates are inclined at an angle of 45°. Each clarifier, designed for a surface loading rate of 5 m $hour^{-1}$ was sized to have a volume of 50 m^3. Reynolds number was less than 1000 and Froude number was greater than 10^{-5} (Hendricks, 2006). Energy consuming units for the process were sludge transfer pumps. The sludge was transferred to two sludge storage basins to be further treated by the filter presses. Two filter presses are provided. The sludge undergoes solid/liquid separation using one of the filter presses; the other press is used as a backup. The filter press was sized for a belt width of 1 m, whereas the capacity of the press was found to be 0.3 m^3. Based on the characteristics of the sludge cake and waste filtrate produced in the dewatering operation, both were classified as non-hazardous. The sludge cake was transported to a landfill for disposal, while the filtrate was disposed off in the sewer.

Total energy consumption of the DWTP was 5.6 MWh day^{-1}, which consisted of energy consumption for the water treatment units (113 kWh day^{-1}) and the booster pumps (5.5 kWh day^{-1}). The motor sizes determined for the DWTP were validated against the actual motor sizes of the plant. The data was provided by the DWTP managers and was found to be in good agreement with the estimated sizes.

As shown by Figure 3.2, overall, booster pumps, and the unit processes of the DWTP utilize about 98% and 2% of the overall energy consumption of the DWTP, respectively. Hence the largest consumer of energy is the pumping operation for the DWTP (Figure 3.2, Table 3.4), corresponding to 80.5 kWh day^{-1} for the pumping operation within the plant and 5.5 kWh day^{-1} for booster pumps for water storage.

The second largest consumer of energy is the process of lime addition that consisted of lime mixing and lime feed pumps, expending 30% of the total energy consumption, followed by filtration, which consumes about 23% of the total 113 kWh day^{-1} energy consumption of the water treatment units. Largest specific energy consumption was found to be 0.58×10^{-3} kWh m^{-3} for backwash water transfer pumps as well as filter press, and 0.63×10^{-3} kWh m^{-3} for lime feed pumps (Table 3.4). Overall, for the water treatment units, the energy intensity was determined to be 3.1×10^{-3} kWh m^{-3}. Processes involving residual management that included the operation of lamella clarifier, filter press and reclaimed water pumps were found to utilize 40% of the overall energy consumption of the DWTP.

Sensitivity analysis was performed for the energy consumption estimates related to pumping operation for the treatment plant. Wire-to-electric efficiencies of the pumps were increased by 5%

and 10%, which resulted in 4.8% (107.5 kWh day^{-1}) and 9.1% (102.6 kWh day^{-1}) decrease in the total energy consumption (113 kWh day^{-1}) of the water treatment units respectively. Whereas decreasing wire-to water efficiencies by 5% (118.8 kWh day^{-1}) and 10% (125.4 kWh day^{-1}) resulted in increased total energy consumption by 5.3% and 11.1%.

Klein et al. (2005) reported on electricity use for a typical urban water system in Northern California; for water supply and transport (0.04 kWh m^{-3}), water treatment (0.026 kWh m^{-3}), and water distribution (0.32 kWh m^{-3}) amounting to approximately 0.38 kWh m^{-3} total electricity use. This was in contrast to 2.7 kWh m^{-3} of electricity use for Southern California; mainly due to the difference in electricity use for water conveyance in Northern California (0.04 kWh m^{-3}), and Southern California (2.35 kWh m^{-3}). This is the case because the source of half of the water supply to Southern California is the Colorado River and State Water Project, which have long transportation distances. Plappally and Lienhard, (2012) conducted a literature review of various water related life cycle processes and the associated energy requirements. The study reported energy consumption of various energy driving units of water treatment processes and operations. This included rapid mixers for coagulation (0.008–0.022 kWh m^{-3}), dissolved air flotation system ($9.5x10^{-3}$–$35.5x10^{-3}$ kW h m^{-3}), gravity filtration (0.005–0.014 kWh m^{-3}) and ozone generation (0.2kWh m^{-3}).

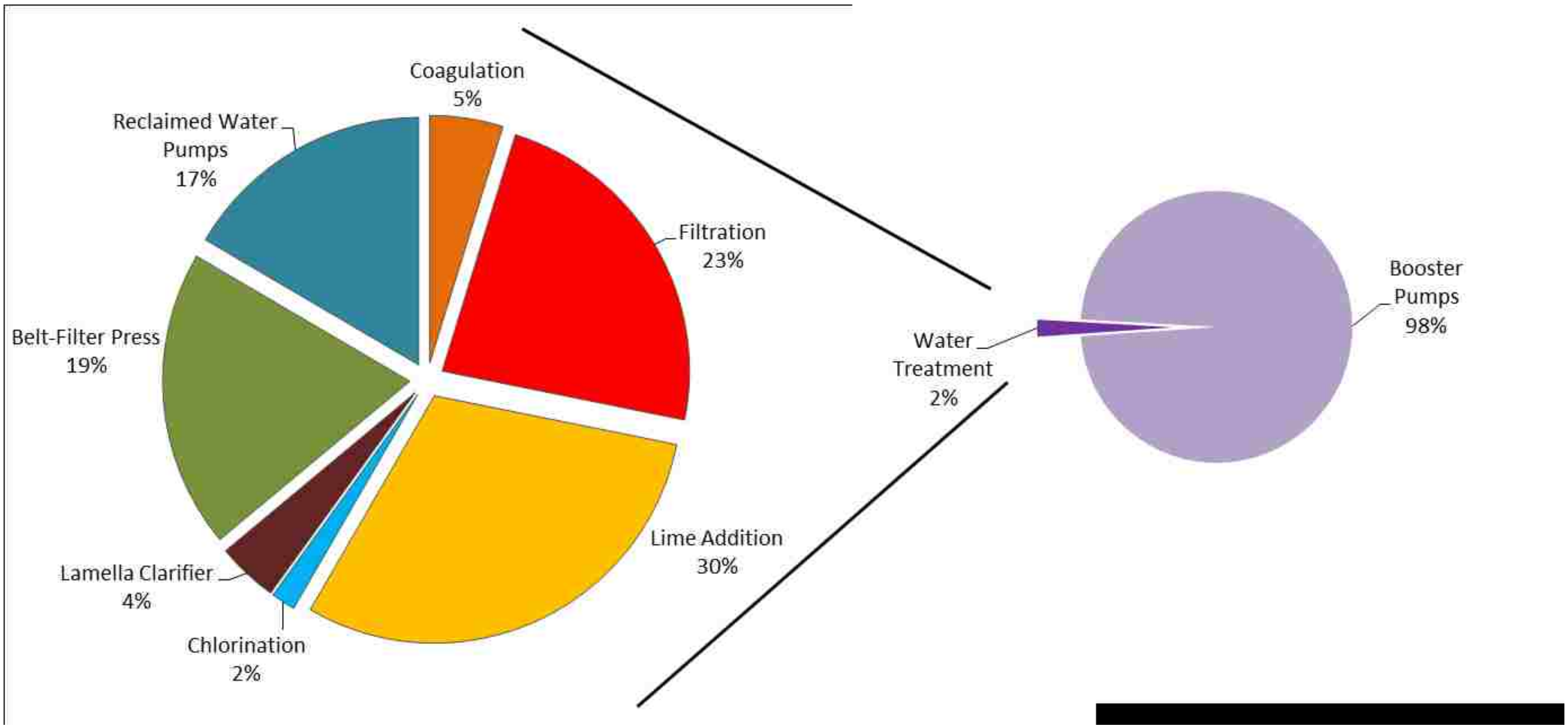


Figure 3.2: Energy consumption percentage for the water treatment units and the booster pumps.

3.5.2 System Advisor Model

Energy consumption associated with the unit processes of the DWTP and the booster pumps for water distribution was used as the electric load input for SAM. Electricity rate structure for the DWTP was downloaded from the utility rate database provided for SAM. The rate structure was applied was that of commercial facilities with a demand range of 50 kW-500kW or for energy consumption greater than 10,000 kWh per month.

Characteristics of the solar PV system utilized in the study are shown in Table 3.5. The module and the inverter were selected from the database provided by SAM. A multi-crystalline silicone module was used with an efficiency of 15.6%. Crystalline-silicone solar panels are more expensive but also more efficient compared to other types of panels. A solar system generates DC electricity, which is converted into AC electricity using an inverter. Sunpower: SPR-4000 was the grid-tied interactive inverter utilized for this study. The inverter's efficiency is 95% whereas the maximum DC power rating is 4200 Watts. Since the treatment plant operates 24 hours per day, battery storage was provided to meet energy requirements in the absence of sunlight. The battery storage selected was lead acid absorbent glass mat (AGM) battery, which is a valve-regulated, low maintenance 1200 Ah battery. The selected PV system characteristics and costs were found in the literature (Solarpenny, 2017; Realgood, 2017; Wholesalesolar, 2017a) and incorporated into SAM for the analysis.

Table 3.5: Photovoltaic system design characteristics used in SAM.

	Parameter	Unit	Value
Module	Module Name	-	Centrosolar America BP6-260BB
	Module Area	m²	1.637
	Module Material	-	Multi C-Si
	Nominal Efficiency	%	15.9
	Maximum Power Pmp	Watt	260
	Maximum Power Voltage Vmp	Volt	31.1
	Maximum Power Current Imp	Ampere	8.4
	Open Circuit Voltage Voc	Volt	37.8
	Short Circuit Voltage Isc	Ampere	8.9
Inverter	Inverter Name	-	Sunpower: SPR-4000
	Weighted Efficiency	%	95.4
	Maximum AC Power	Watt	4000
	Maximum DC Power	Watt	4198
	Nominal AC Voltage	Volt	240
	Maximum DC Voltage	Volt	480
	Maximum DC Current	Ampere	0.008
	Minimum MPPT DC voltage	Volt	100
	Nominal DC Voltage	Volt	300
	Maximum MPPT DC Voltage	Volt	480
Battery Storage	Battery Name	-	Lead Acid AGM
	Cell nominal voltage	Volt	2
	Internal Resistance	m Ohm	2
	Cell Capacity	Ah	1200
	Minimum State of Charge	%	10
	Maximum State of Charge	%	95
	Minimum Time at Charge State	min	10
	Battery Bank Replacement Cost	$ kWh^{-1}	110

Various losses were also incorporated in this study including average annual soiling loss (3%), connection losses (0.5%), DC wiring losses (2%), AC wiring losses (1 %) and system's performance degradation rate (0.5%). SAM's default values for losses were utilized for this study.

Two-axis tracking system was used. Tracking systems follow the sun, maintain PV panels at optimum tilt angles, and maximize energy production. Self-shading analysis was performed manually using the criteria provided by Brownson, (2013) and ground coverage ratio of 0.3 was shown to minimize self -shading. Weather information was one of the inputs for SAM, which includes information related to solar insolation (Stephen et al. 2010). Typical Meteorological Year TMY3 weather information for the location was used as an input. Annual direct beam insolation was about 6.8 kWh m^{-2} day^{-1}. Global, beam and diffuse irradiance for the selected location is shown in Figure 3.3.

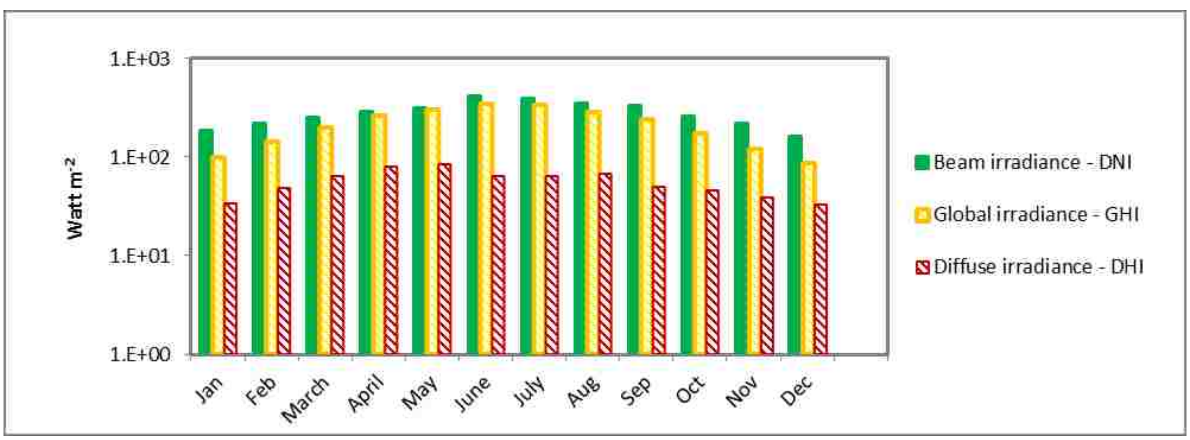


Figure 3.3: Global, beam and diffuse irradiance for the selected location.

Various financial parameters were utilized as an input to SAM to evaluate the viability of solar PV including direct and indirect costs, O&M costs, loan amount, interest rate, loan period, analysis period, inflation rate, discount rate, taxes, and salvage value.

Sales tax is applied on the direct costs and the tax value is determined by the state. Since it becomes part of the total costs, it influenced the estimation of NPV and LCOE. Property tax payment based on the assessed value of the property was a tax-deductible expense in the model. Property tax amount is the product of property tax rate and assessed value of the property. Property tax rate stays constant in SAM, but assessed value of property changes at the specified rate, called assessed value decline. For year one, the assessed value is the product of assessed percent and total installed cost. For subsequent years, assessed value is based on assessed value decline. For an assessed value decline of zero percentage, the assessed value of property does not decline. State and federal incentives can be claimed (DSIRE, 2017) and were incorporated into the analysis. Property tax exemption was applied for this analysis, which was a state incentive. Because of the conditions stipulated in the property tax exemption incentive, other state incentives could not be claimed. For example, partial sales tax reduction to 2.6% could not be claimed since state incentive of property tax exemption was being claimed by the solar PV system. Federal investment tax credit (ITC) of 30% was also included in the analysis. Solar projects placed after 2022, can claim ITC of 10% only.

A fixed yearly O&M cost of \$15 kW^{-1} $year^{-1}$ was specified that increased annually corresponding to the inflation rate of 2.5%. Insurance costs were tax-deductible expense, calculated as the product of insurance rate and total installed cost, increasing annually based on inflation rate. Salvage value (McCabe, 2011) was also specified but appeared only in the final year cash flow of the PV system. Debt amount equaled the installed costs for this analysis.

For depreciation calculations, SAM provides the option of selecting 5-year MACRS (Modified Accelerated Cost Recovery System) or straight-line depreciation methods that are offered by the Federal government and some states. SAM also provided the option of manual input of depreciation percentages. There was also the option of not claiming any depreciation in SAM. For this analysis, 5-year MACR option was selected as it is offered by the state in which the DWTP is located. Since 30% investment tax credit was being claimed for this analysis, the DWTP was eligible for 5-year MACR.

Results for the techno-economic analysis using SAM are shown in Table 3.6. PV system was designed with battery storage that would meet 100% of the load for 24-hour duration of the day, and thus can be used as a stand-alone system. Analysis showed that the DWTP would require a 1.5 MW PV system with a large battery bank capacity of 30.2 MWh to offset its energy requirements for 24-hour duration of the day. Net present value was found to be positive as shown in Table 3.6. Net capital costs for installing solar PV for the DWTP amounted to $9 million. Figure 3.4 shows the electric load input and PV system AC energy output for DWTP. Various studies predict a decrease in battery storage costs (Berckmans et al. 2017; Kittner et al. 2017; Nykvist & Nilsson, 2015). Kittner et al. (2017) forecasted the battery storage costs to fall by 39% between the years 2016-2020. In this study, the battery bank was replaced after 13 years and the battery replacement cost was reduced by 30% as a conservative estimate. Further, if the same PV system was grid-connected and no battery storage was provided it would offset about 60% of the total load, with a NPV of $1 million (Table 3.4), showing the effect of the battery storage on the performance and cost of the system.

Table 3.6: Solar PV system technical and economic analysis results generated by using SAM for the drinking water treatment plant.

	Parameter	Unit	Standalone PV System with Battery Storage (100% of electric load offset)	Grid-connected PV with No Battery Storage (60% of electric load offset)
Module	Nameplate Capacity	kW	1500	1,500
	Number of Modules	-	5769	5769
	Modules per String	-	9	9
	Strings in parallel	-	641	641
	Total Module Area	$x10^3$ m²	9.4	9.4
	String Voc	Volt	340	340
	String Vmp	Volt	280	280
	Total Land Area	$x10^3$ m²	31.6	31.6
Inverter	Total Capacity	kWac	1248	1248
	Number of inverters	-	312	312
	Maximum DC Voltage	Volt	480	480
	Minimum MPPT Voltage	Volt	100	100
	Maximum MPPT Voltage	Volt	480	480
	DC to AC Ratio	-	1.2	1.2
Battery	Nominal Bank Capacity	MWh	30.2	-
	Nominal Bank Voltage	$x10^3$ Volt	350	-
	Cell in Series	-	175	-
	Strings in Parallel	-	72	-
	Battery efficiency	%	89.6	-
Financial Metrics	Net Present Value	$ million	0.56	1.05
	Levelized cost of electricity (nominal)	Cents kWh^{-1}	3.05	0.48
	Levelized cost of electricity (real)	Cents kWh^{-1}	2.47	0.39
	Net Capital Cost	$ million	9.04	3.8
	Electricity bill without system (year 1)	$	206,040	206,040
	Electricity bill with system (year 1)	$	192	46,684

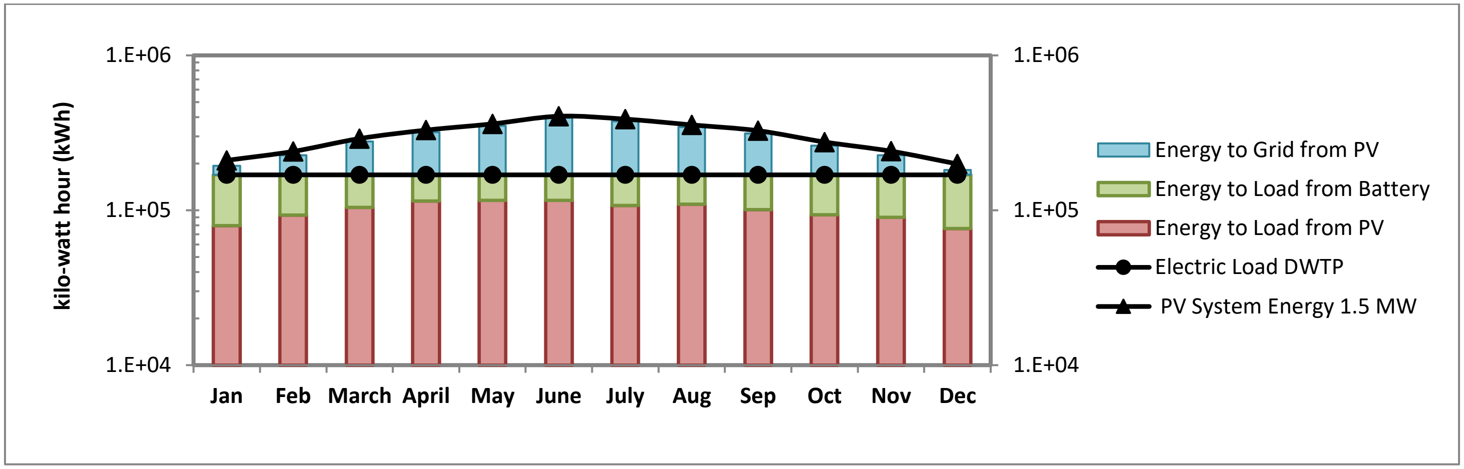


Figure 3.4: Electric load input and PV System AC energy output for drinking water treatment plant.

Solar PV was successfully able to offset the energy requirements of the DWTP. Grid electricity was used as a back-up system for solar PV since it is required by law to provide back-up for any electricity generation system; hence there are still the fixed monthly charges to be paid as shown by the amount for Table 3.6. Providing other types of back-up system for electricity generation will be much more expensive.

NPV for the DWTP was found to be positive, thus installation of distributed solar was found to be economically feasible. Real and nominal LOCE was found to be 2.47 and 3.05 cents kWh^{-1} for the DWTP, respectively (Table 3.6).

Figures 3.5 and 3.6 show the effect of discount rate and interest rate on LCOE and NPV, for the DWTP. As shown by Figure 3.5, as interest rate increases, the value of LCOE increases and NPV decreases. Change in interest rate between 0-5%, increased the real LCOE between 0.16-4.33 cents kWh^{-1}, while the NPV changed between positive \$1.4 million to negative \$0.12 million. As shown by Figure 3.6, an increase in discount rate decreases the LCOE value and increases NPV. Changes in discount rate between 5-10%, changed the NPV between negative 0.32 million to positive \$0.96 million for the DWTP.

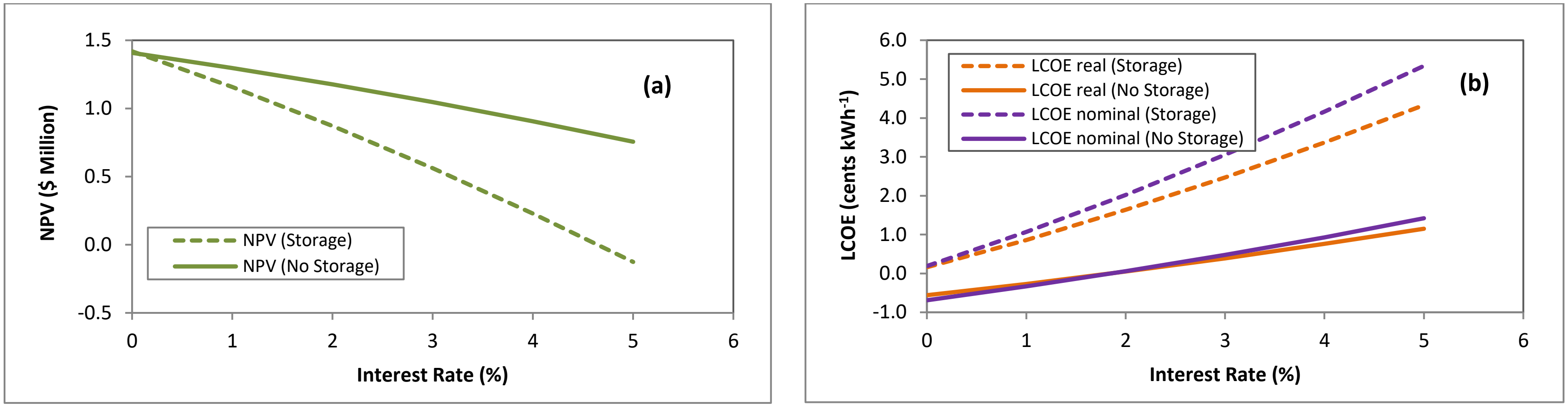


Figure 3.5: Quantifying the influence of interest rate on (a) NPV and (b) LCOE of the drinking water treatment plant. Dotted line donates PV system with battery storages, and firm line donates similar capacity PV system with no battery storage.

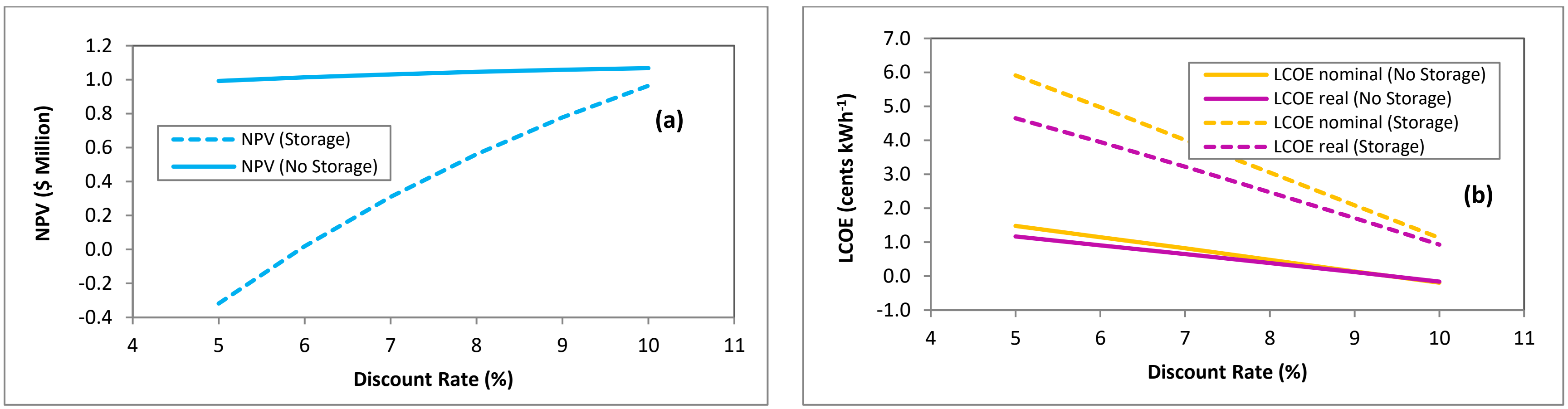


Figure 3.6: Quantifying the influence of discount rate on (a) NPV and (b) LCOE of the drinking water treatment plant. Dotted line donates PV system with battery storages, and firm line donates similar capacity PV system with no battery storage.

To check if the PV system with battery storage achieved grid-parity, the federal and state incentives were removed for the economic assessment, and nominal LCOE was estimated. This value was compared against the average price of electricity for commercial consumers using grid-connected electricity which was about 7.98 and 8.08 cents kWh^{-1} for the years 2016 and 2017, respectively (USEIA, 2017a). Hence, to check for grid price parity, economic assessment was made by not incorporating the 30% ITC as well as the property tax exemption incentive. It was found that if 30% ITC is not incorporated, NPV was negative $1.9 million rendering the PV installation economically unfeasible, while the nominal LCOE was estimated as 10.73 cents kWh^{-1} for the DWTP. If property tax exemption was not applied for the analysis then the nominal LCOE was 4.88 cents kWh^{-1} while the NPV decreased but remained positive at about $ 0.01million. For property tax evaluation, the assessed value was taken as 35% of the taxable value of the property while the property tax rate used was 2.8% as stipulated by the state. If property tax exemption as well as the 30% ITC were not incorporated into the analysis, NPV was negative $2.1 million and the nominal LCOE was computed as 12.08 cents kWh^{-1} for the DWTP. Hence, for the DWTP, grid price parity was not achieved. So far, successful deployment of solar PV still heavily depends on governmental support.

Fu et al. (2017) estimated LCOE values for commercial solar PV in the U.S., and reported that between the years 2010 and 2017, without including the 30% ITC, the LOCE value ranged between 9 cents kWh^{-1} and 12 cents kWh^{-1}. When 30% ITC was incorporated in the estimations, the LCOE value ranged between 6 cents kWh^{-1} and 8 cents kWh^{-1}.

LCOE and NPV used for the economic assessment of a project have their shortcomings. The parameter of NPV does not take into account the scale of investment and heavily relies on the value of discount factor. LCOE is dependent upon various financial parameters and hence any error in assuming those financial parameters will affect the true LCOE estimate. However, both these parameters are heavily used by investors to determine the viability of a project (Mohanty et al. 2015).

Net metering was not incorporated for this facility. The electric utility operating in the selected area allowed net metering for residential and commercial facilities with PV systems of 1 MW or less, and energy consumption of less than 10,000 kWh per month. Even though net metering was not incorporated for the analysis, it was found that the project was financially feasible with positive NPV. This presents promising implications for solar PV.

For development of solar PV, land area requirements were found to be 0.03 km^2 for the DWTP, equivalent to 6 football fields (Table 3.6). The existing landholdings of the treatment plant were estimated using ArcMap as 0.17 km^2. Hence, sufficient landholdings were available for the development of solar PV, and land acquirement was not required for development of distributed solar. Land utilized for the analysis was relatively flat with low shrubs and grass; hence, existing condition of the land area did not warrant significant work related to land preparation for solar development.

Provision of incentives could be a motivating factor for water sector to incorporate renewables into the design of water infrastructure. This will help achieve sustainability goals of the water industry and improve the overall health and well-being of the community and the environment. Government policies and incentives help in removing the financial barriers, facilitate solar power development and boosts investment in renewable projects (Sawin et al. 2016; Nemet et al. 2017;

Ozoegwu et al. 2017; Timilsina & Kurdgelashvili, 2017). Various states in the U.S have enforced renewable portfolio standards (RPS) that encourages and regulates the use of renewables and energy efficient technologies (DSIRE 2017). Some countries have implemented priority dispatch for electricity generated by renewables causing electricity production due to thermoelectric power plants unprofitable (Ramírez et al. 2017). Feed-in-tariffs and net metering encourages the installation of renewables (Chapman et al. 2017; del Río et al. 2017). The current treatment plant could not qualify for net metering; such regulatory restrictions have the potential to deter investments for distributed solar projects.

There is a growing trend for energy-intensive water treatment. However, there are growing concerns for energy use for water-related operations. Using solar energy to offset energy requirements of a water treatment plant can help incorporate sustainability goals for water-related operations. Integrated planning and policy-making is required for energy-intensive water operations as well as water-intensive energy operations (Dai et al. 2017, Fang & Chen, 2017; Liu et al. 2017).

Technological improvements have increased the energy output of the solar panels and decreased the costs, a trend which is predicted to continue in the future. NREL, (2017) maintains an up-to-date database of efficiency improvements in the field of solar PV. Green et al. (2017) have also reported on up-to-date solar PV efficiencies. Ongoing research is focusing on different areas that include discovering higher efficiency solar cell materials, as well as for minimizing efficiency losses for existing PV technologies, that can be manufactured cost-effectively on a commercial scale. Battery storage prices continue to fall as well. For now, battery prices remain relatively costly (Soshinskaya et al. 2014). So far successful deployment of solar still largely depends on federal and state incentives to make it economically beneficial, as in the case of this study. The successful solar energy projects pursued in recent years are grid-connected photovoltaic systems, especially those coupled with energy storage, and they are the driving force behind the success of solar energy (Timilsina & Kurdgelashvili, 2017; Ma et al. 2017).

Carvalho et al. (2013) assessed the technical and economic feasibility of using photovoltaic-based water treatment (using reverse osmosis) and pumping system in semi-arid Fortaleza, Brazil. The study found that the optimum system configuration would involve a cutoff concentration of 2,748 mg l^{-1} of brackish water, using PV panels with no battery storage resulted in a drinking water production of production of 175 liter day^{-1} at 324.60 mg l^{-1} salt concentration. Jones et al. (2016) conducted economic feasibility of three power sources (grid, diesel, PV) for well pumping and desalination of brackish groundwater in Jordan Valley. The study found the PV-powered system to be more cost-effective when compared to diesel-powered system, but less cost-effective compared to a grid-connected system.

Loizidou et al. (2015) analyzed the technical feasibility of brackish water treatment for a small village in Jordan with no access to electricity. A hybrid energy system was proposed, comprised of 2 kW solar PV, a 10 kW wind system, and a 13 kW hydro-system. The energy system powered reverse osmosis treatment of the brackish water, resulting in the production of 40 m^3 day^{-1} of drinking water with a conductivity of less than 400 μS cm^{-1} in compliance with World Health Organization standards.

3.5.3 Carbon Emissions

Incorporating distributed solar can lead to decarbonization of water treatment operations. Net reduction in carbon emissions was found to be 950 and 570 metric ton CO_2eq $year^{-1}$ for the DWTP with and without battery storage, respectively. Even though initial investment costs for solar PV are large, the reduction in emissions due to their development, leads to a healthier community and the environment. For water distribution in Las Vegas Valley, Shrestha et al. (2012) reported an energy expenditure of 0.85 million MWh year^{-1}, resulting in about 0.53 billion kg CO_2 emissions annually. The study also projected an increase in energy use of 1.34 million MWh year^{-1} by the year 2035, contributing about 0.84 billion kg year^{-1} of CO_2 emissions (Shrestha et al. 2012).

For estimation of carbon emissions, state's electricity source mix was utilized. In reality, during peak power hours of the day, PV could be offsetting peak power (perhaps natural gas) instead of baseload power (perhaps coal). These two fuels have very different carbon emissions (as discussed in section 3.3), but due to unavailability of this data, grid mix average was used.

3.6 Conclusion

The purpose of this study was to conduct the technical and economic assessment of using solar PV for a small DWTP. Energy consumption of unit processes of the plant was determined and then the total load was used as an input for the PV system design. Technical and economic assessment of the PV system was conducted using SAM based on available land acreage of the plant as well as the economics of the system. Reduction in carbon emissions due to development of the PV system was also estimated.

The energy consumption of the DWTP was determined. It was found that:

- The pumping operation was the largest consumer of energy. Energy consumption was largest for the booster pumps for water storage (0.55 MWh MG^{-1}).

- The treatment of the drinking water (excluding booster pumps) utilized 2 % of the total energy consumption. Overall, lime addition (2.4 kWh MG^{-1}) and filtration process (2.2 kWh MG^{-1}) were the largest consumers of energy for the water treatment units.
- Energy intensity estimates could be used to compare performance of the plant against other plants. The design equations used for this study could also be applied to determine the energy consumption of other plants.

Based on the energy consumption and existing land holdings of the DWTP, techno-economic assessment of the proposed PV system was conducted. It was found that:

- DWTP would require a 1.5 MW PV system with a battery bank capacity of 30.2 MWh having the potential to act as a standalone system. PV system with similar capacity but without battery storage was able to offset approximately 60% of the electric load.
- Land requirements (0.03 km^2) for the PV system were much smaller compared to the existing landholdings of the plant (0.17 km^2).
- Development of solar PV was found to be economically feasible. LCOE for the PV system in standalone mode was found as 2.5 cents kWh^{-1}. However, grid price parity was not achieved for the PV system.
- Net reduction in carbon emissions was found to be 950 and 570 metric ton CO_2eq $year^{-1}$ for the DWTP with and without battery storage, respectively.

CHAPTER 4: INCORPORATING SOLAR TO OFFSET THE ENERGY CONSUMPTION OF A 90 MGD DRINKING WATER TREATMENT PLANT

This chapter deals with meeting objective two of this research concerning a 90 MGD water treatment plant located in the southwest; by first studying the water-energy nexus of the plant, determining the unit-process based energy consumption of the plant and then offsetting the energy consumption by using solar PV, based on economic feasibility and existing landholdings of the plant.

4.1 Introduction

Energy conservation and sustainability is one of the pressing issues being faced by water industry today (Spellman, 2013). Energy usage associated with the drinking water and wastewater facilities account for 3-4% of the United States total energy use (Spellman, 2013; WEF, 2009; Goldstein and Smith, 2002) resulting in the emission of about 40.8 billion kg of GHG (USEPA, 2013). Eighty percent of this energy use is for conveying or pumping the water and wastewater and the remaining is used for water treatment (Goldstein and Smith, 2002).

Energy use related to drinking water treatment may include energy for water conveyance, energy for the unit operations and processes of the treatment plant, for the building and facility related equipment (lighting, heating and ventilation), and energy for water distribution (Shrestha et al. 2011; Shrestha et al. 2012). Energy use for water treatment depends on various factors such as raw water quality, water source, age of water delivery system, conveyance distance, water storage capacities, as well as elevation differences (Spellman 2013).

Future energy demands related to water treatment are expected to grow because of various reasons. Population growth places increased demand on water supply systems. Energy expenditure of water operations increases due to population growth (Loizidou et al. 2015) as well as aging infrastructure (Chae and Kang, 2013; USEPA, 2016a). Further, pollution is caused by emission of greenhouse gases, due to the burning of carbon-based fuels for electricity generation (Molinos-Senante & Guzmán, 2016; Xue et al. 2016). These can be motivating factors for DWTPs to explore and implement different methods to reduce their overall energy consumption. Changing climate complicates the matter further (Bukhary et al. 2014, Bukhary et al. 2015; Choubin et al., 2014; Nussbaum et al. 2015; Pathak et al. 2016a&b, 2017; Sagarika et al. 2014, 2015a&b; Tamaddun et al. 2016, 2017). Changes in temperature and increased drought /flood conditions may result in the degradation of source water. Also in recent times, with technological advancement and introduction of new chemicals into the environment, there has been an increased emphasis on stringent water quality standards, enforced by the implementation of various regulations (Crittenden et al. 2012), although enforcement of such standards may not be possible today because of high costs of treatment associated with it (Qu et al. 2013). Employing alternate ways to generate energy such as using renewables or using energy conservation measures can help in cost reduction (USEPA, 2016a).

Various studies have evaluated the energy consumption for drinking water treatment (Bukhary et al. 2017a; Bukhary et al. 2017b; Molinos-Senante & Sala-Garrido, 2017; Vadasarukkai & Gagnon, 2017; Wakeel et al. 2016; Plappally and Lienhard 2012) and wastewater treatment plants (Gil-Carrera et al. 2013; Bailey 2012; Chang et al. 2017; Gude 2015; Huggins et al. 2013; Kavvada et al. 2016; Krzeminski et al. 2012; Mamais et al. 2015; Mizuta & Shimada 2010; Newell, 2012; Panepinto et al. 2016; Smith et al. 2014; Stillwell et al. 2010). As can be seen, more studies exist for evaluating wastewater treatment plant compared to drinking water treatment plant.

Studies for evaluating of the energy consumption of existing DWTPs are limited. Wakeel et al. (2016) conducted a literature review and compared energy consumption of a conventional water treatment in various countries including Australia (0.01–0.2 kWh m^{-3}), Spain (0.11–1.5 kWh m^{-3}), New Zealand (0.15–0.44 kWh m^{-3}), U.S. (0.184–0.47 kWh m^{-3}), Canada (0.38–1.33 kWh m^{-3}), and Taiwan (0.16–0.25 kWh m^{-3}). Similar studies were also conducted by Plappally and Lienhard, (2012). Bukhary et al. (2017b) determined energy consumption of a 4.5 MGD DWTP located in Jamshoro Pakistan, as 7.4 Wh m^{-3}. The largest consumer of energy was the chlorination process, because of on-site generation of chlorine dioxide, consuming about 34% of the total energy consumption of the DWTP. Coagulation process consuming about 31% of the total energy consumption was the second largest consumer of energy. Vadasarukkai & Gagnon, (2017) studied the effects of mixing intensity on floc formation as well as the associated energy consumption.

One of the ways to achieve energy conservation is by using alternative energy for various water related operations (Mekonnen et al. 2016). Renewable energy resources including solar, wind, biomass can be used to generate energy for water resources systems, including water treatment processes, wastewater treatment processes and water pumping. This will lead to a decrease in fossil fuel based energy requirements.

Solar energy is gaining popularity as a clean source of energy production. Sunlight is an abundant resource especially in the southwest and application of this technology on an industrial scale will not only help towards energy independence, but will lead to the reduction in GHG emissions (Bukhary et al. 2017c, Bukhary et al 2016; Chatzisideris et al. 2016; Wu et al. 2017). During operation, solar energy has zero carbon emissions but there are some emissions generated during construction and transportation of solar systems. Solar energy is vital to human life, and has been harnessed by humankind for thousands of years.

Solar energy can be broadly categorized as CSP and PV. CSP systems, typically deployed at utility-scale, utilize solar thermal energy for electricity generation. Solar PV technology generates electricity by converting sunlight directly into electricity by utilizing the photoelectric effect and the photovoltaic effect. Solar PV can be deployed at utility, commercial and residential scale, as decentralized as well as grid-connected systems (Okoye & Oranekwu-Okoye, 2017). Using PV has an additional advantage of being able to supply a balanced and sustainable power throughout the day even at the time of peak demand when electric power is the most costly. Performance of the PV system may be affected by cloud cover, which can be overcome by using energy storage systems.

Deployment of solar energy depends on financial feasibility since it entails large capital costs. There are also recurring costs for O&M, and government taxes, paid over the life of the project (Ferreira et al. 2018; Linssen et al. 2017; Mundada et al. 2017). Different incentives and policies help dissipate these costs and make solar energy economically competitive with other sources of energy generation (DSIRE, 2017). The costs associated with solar installations can also be dissipated due to the corresponding reduction in carbon emissions, leading to an improved health of the community and the environment (Buonocore et al 2017; Brown et al. 2017; Prehoda & Pearce, 2017).

Application of solar energy depends on land availability, and the deployment requires large land area (Bukhary et al. 2017c, Nonhebel, 2005). PV systems can be ground-mounted or deployed on rooftops. The existing landholdings of the treatment plant can be utilized for the installation of solar energy (Bukhary et al. 2017a, Bukhary et al. 2017b). Treatment plants are provided with sufficient land acreage based on anticipated future development and redevelopment. Water treatment plants are usually located upstream of the community they serve while wastewater plants are located downstream of the community. If the landholdings of the treatment plant are not sufficient, then the land area would need to be acquired.

Solar energy has great potential as a clean source of energy for water treatment processes (García-Vaquero et al. 2014; Soshinskaya et al. 2014), wastewater treatment processes (Astolfi et al. 2017; Bustamante & Liao 2017; Gikas & Tsoutsos, 2015; Han et al. 2013; Souza et al. 2015; Valero et al. 2010; Zhang et al. 2013) and desalination (Alghoul et al. 2016; Bouchekima 2003a; Bouchekima 2003b; Fthenakis et al. 2016; Loizidou et al. 2015; Shalaby 2017; Shawky e. al. 2015; Xu et al. 2017; Zhang & Li, 2017, Zhang et al. 2018). Studies for evaluating of the potential of existing DWTP for incorporating solar energy technologies are limited. García-Vaquero et al. (2014) made performance comparisons between a conventional DWTP and a wind-solar-powered nano-filtration pilot plant located in Spain. Soshinskaya et al. (2014) explored the potential of using wind and solar energy for a large-scale water treatment plant in Netherland. The limited existing literature analyzed the yearly energy consumption of the DWTP without going in detail regarding the energy consumption of each unit operation involved in the treatment.

The goal of this study was to offset the energy consumption by using solar technology for an existing 90 million gallons per day (MGD) DWTP by:

(a) Determining the energy consumption of each unit operation in the treatment plant,

(b) Sizing the DWTP to offset the energy consumption of the plant for solar PV based on available land holdings and economic feasibility and

(c) Determining the net reduction in carbon emissions by installing solar PV compared to non-PV based design.

With the aim of incorporating sustainability in DWTP in southwestern U.S., the study provides a roadmap for using solar PV for an existing DWTP, leading to reduction in carbon emissions and ultimately reduced energy costs. The approach used in this study can be utilized to analyze unit processes of other DWTP based on energy consumption, with the long-term goal of energy independence and sustainability.

4.2 Study Area

For this study, the selected treatment plant was located in a city with a population of 0.24 million and covering a land area of 266.8 km^2 (U.S. Census, 2015). The average total precipitation was 183.4 mm and the average maximum and minimum temperature were 19.6°C and 1.4°C respectively (WRCC, 2016).

Primary source of water supply for the city was a river originating from a lake, enduring a 161 km course through different canyons, and ultimately having an outfall in another lake. Only 6% of the water, flowing through the river was used by the community; in addition, almost half of that is returned to the river after the generated wastewater was treated at the wastewater treatment plants. Hence, only 3% of the water flowing through the river was used in a non-drought year, while 8% in a drought year. The selected DWTP had the capacity to treat 90 MGD of water.

4.3 Data Sources

Data sources used for this study are discussed as follows.

4.3.1 Process flow Diagram

Process flow diagram was acquired from the treatment plant managers. The process flow diagram discussed in this section for DWTP is based on the information provided.

Figure 4.1 shows the process flow diagram for 90 MGD Water Treatment Plant that utilized conventional treatment train. Raw water from the river at first underwent pre-treatment and passed through bar screens, raw water basins and then automatic screens for removal of larger debris, settlement of heavier grit, and removal of smaller debris respectively. Then the water was coagulated and flocculated. Next, the water was filtered through dual-media filters. Lastly, the water was disinfected by application of sodium hypochlorite and then stored for distribution throughout the city.

4.3.2 Water Quality Report

Raw water quality report was acquired from the selected DWTP managers, and any missing data was partially reproduced from Crittenden et al. (2005). Raw water source was a river. The design for each unit process is dependent upon the raw water characteristics as well as the corresponding maximum contaminant levels (MCL) and secondary maximum contaminant levels (SMCL) determined by U.S. Environmental Protection Agency (USEPA) as shown in Table 4.1 (USEPA, 2016c).

4.3.3 Treatment Plant Design Criteria

Sizing was achieved by using industry accepted design criteria (WEF, 2010; Reynold and Richards, 1996; Crittenden et al. 2005, Hendricks 2016).The design criteria is discussed in detail in the methodology section.

4.3.4 Available landholding

For the DWTP, the available landholdings were estimated using ArcGIS.

4.3.5 Federal and State Incentives

Federal and state incentives were obtained from Database of State Incentives for Renewables & Efficiency (DSIRE) (DSIRE, 2017). These incentives were applied during analysis to determine economic feasibility of project.

Federal investment tax credit (ITC) was also applied to the economic analysis. It represents a percentage of investments that the owners are allowed to deduct from their taxes, dollar-to-dollar. For solar projects of commercial, industrial or agricultural nature, placed before or during the year 2019, can claim 30% ITC, while 26%, 22% and 10% ITC can be claimed by projects placed during 2020, 2021, and 2022 year and onwards, respectively. If federal taxes owed are less than 30% of installed costs, solar PV owners owe no taxes for that year, and any unused tax credit is carried over to the next year. A state property tax exemption incentive was also incorporated into the economic analysis. The exemption was applicable for the design life of solar PV. This incentive cannot be claimed if another state tax abatement or exemption is claimed by the same building. Hence, only these two incentives were incorporated in the analysis.

4.3.6 Carbon Emissions

Data sources and parameters for carbon emissions and southwestern state's energy-source mix for electricity generation is shown in Table 4.2. Carbon emissions data in units of $gCO_2eq\ kWh^{-1}$, for different energy sources for electricity generation, was obtained from Moomaw et al. (2011). State's electricity source mix for various energy sources was obtained from USEIA (USEIA, 2016d) and was assumed constant for the analysis period because the information was not available for that period.

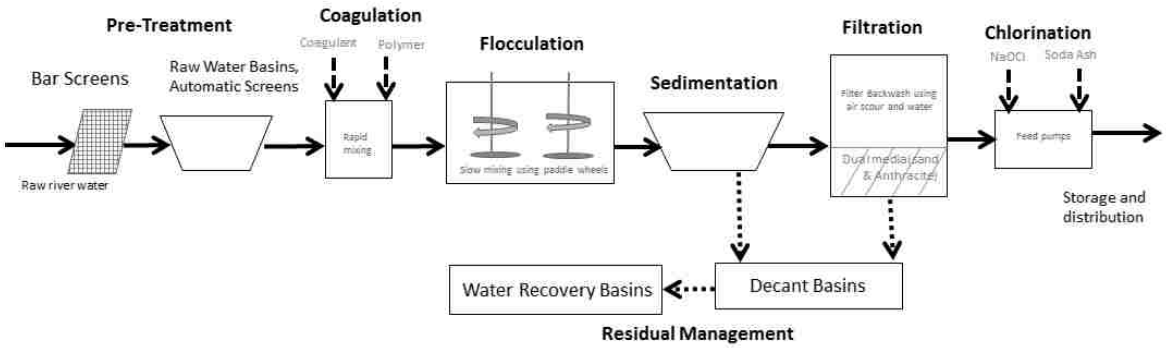


Figure 4.1: Process flow diagram for the selected drinking water treatment facility. Solid arrows determine the progression of water treatment; dashed arrows determine the chemical injection points, while dotted arrows determine the progression for residual management.

Table 4.1: Water quality report obtained from the drinking water treatment facility managers.

Parameter	Units	Average value	USEPA *MCL/ **SMCL/ guidelines
pH	N/A	8.2	6.5-8.5
Water temperature (winter)	°C	5	Not regulated
Water temperature (summer)	°C	19	Not regulated
Turbidity	NTU	4	0.3

*MCL: Maximum contaminant level
**SMCL: Secondary maximum contaminant level

Table 4.2: Carbon emissions (obtained from Moomaw et al. 2011) and State's electricity source mix (obtained from USEIA, 2016d) for various energy sources.

Energy Sources for Electricity Generation	Carbon Emissions (gCO_{2eq} kWh^{-1})	State Electricity Source Mix
Coal	1001	23.51
Natural Gas	469	56.41
Petroleum	840	0.07
Nuclear	16	0
Hydropower	4	7.42
Bio-power	18	0.1
Geothermal	45	8.5
Wind	12	0.95
Solar	46	3.04

4.4 Methodology

Current research used solar PV panels to meet the energy requirements of the selected DWTP. Maximum day demand flow, at the end of design period was 90 MGD for the DWTP.

The first step of the current research focused on sizing the DWTP by designing the various unit processes involved. Sizing was achieved by using industry accepted design criteria (WEF, 2010; Reynold and Richards, 1996; Crittenden et al. 2005). Energy driving units for each unit operation were identified and energy consumption in the units of kWh day^{-1} and kWh m^{-3} for each unit operation was individually determined. Computations were made by using Microsoft Excel Spreadsheet. Design of solar PV and the economic analysis was achieved using System Advisor Model (SAM).

Criteria utilized for the design and estimation of energy consumption for each unit processes of the DWTP is summarized as below. It is followed by details of the software SAM, employed to evaluate the techno-economic feasibility of using solar PV to meet the energy demands of the DWTP.

4.1 Design and Energy Consumption for Treatment Plant

4.1.1 Pre-sedimentation:

Pre-sedimentation or raw water basins initiate suspended solids removal and are helpful in equalizing variable turbid loadings entering a treatment plant. Typically, plants treating river water are equipped with raw water basin, since river water is high in turbidity (McKinney, 2004). Two tanks should be provided at a minimum to incorporate redundancy in the system. Surface loading rates vary between 200-400 m^3 m^{-2} day while detention time varies between 6-15 minutes (Crittenden et al. 2005). In the selected DWTP, the pre-sedimentation tanks were cleaned manually.

4.1.2 Coagulation:

Coagulation process utilized in water treatment assists in destabilizing a colloidal suspension, causing collides to agglomerate and form flocs. Coagulants dose and type is dependent upon the results of jar test. For the selected DWTP, ferric sulphate $Fe_2(SO_4)_3$ was used as a coagulant.

After coagulant is added, rapid or flash mixing is required so that the coagulant can uniformly disperse throughout the basin. Mixer can be of various types including mechanical mixers and static mixers. Static mixers are used when mixing is achieved in the conveyance pipe between the coagulant intake pipe and flocculation basin. Mechanical mixing is achieved in coagulation tank whose dimensions of are dependent upon the design of mechanical mixers being used. In this case, static mixer was used. At least two mixers should be provided. Reynold's number > 2000, implies turbulence and good coagulation performance. The design was based on the criteria provided by Hendricks (2006). G value remains a significant parameter for the design of mixers. The equation to compute velocity gradient of a static mixer (Hendricks, 2006) is as follows:

$$G = \sqrt{\frac{P}{\mu V}}$$

Where G= root-mean-square velocity gradient (sec^{-1}), P= power imparted to water (N-m sec^{-1}), V= mixer volume (m^3) and μ=dynamic viscosity (N-s m^{-2}). Dynamic viscosity of water is a function of temperature, while mixer volume is the product of pipe area and length of mixer.

Energy consumption (E) in the units of kWh day^{-1} of the mixers was found using the following equation (Hendricks, 2006).

$$\mathrm{E}\ (kWh\ day^{-1}) = \frac{(\mathrm{G}^2)(\mu)(\mathrm{V})(t_m)}{\mathrm{f}}$$

Where t_m= motor run time (hr day^{-1}), and f= motor efficiency factor. Typically motor efficiency ranges between 0.7-0.9 (Lee & Lin, 2007). For this study, a value of 0.8 was used. Since plant operated 24 hours per day, motor run time of 24 hours was used.

Energy consumption of the metering pump was determined using the brake horsepower (BHP) equation given by Mays, (2005). The BHP equation is as follows:

$$\mathrm{BHP} = \frac{\gamma \mathrm{QH}}{\mathrm{e}}$$

Where bhp = brake horsepower (kW), γ = specific weight (kN m^{-3}), Q = flow rate (m^3 sec^{-1}), H = total dynamic head (m), and e = wire-to-water efficiency. The specific weight of water is dependent upon water temperature. While wire-to-water efficiency can be estimated as the product of pump, motor and drive efficiency.

A jet diffuser pump was used to flash-mix coagulant aid polymer. Power estimations were made by using following equation, based on the criteria provided by Hendricks (2016).

$$P(\mathrm{kW}) = \frac{\mathrm{Q}\gamma \mathrm{g} \mathrm{v}_{\mathrm{jet}}}{2\mathrm{g}}$$

Where v_{jet} is the jet velocity emerging from the orifice (m s^{-1}), g=acceleration due to gravity (9.81 m s^{-2}).

4.1.3 Flocculation

After coagulation, flocculation process involving slow mixing assists in floc formation. These flocs are later separated through the processes of sedimentation and filtration. Coagulation process involves flash mixing to disperse the coagulant within the feed water whereas flocculation process involves slow mixing to enhance the contact between the coagulant and the feed water, and for the subsequent formation of flocs. Slow mixing is required for flocculation, for providing sufficient contact between the coagulant and the particulates suspended within the water.

Paddle wheels were used for flocculation process and the design was based on the criteria provided in Crittenden et al. (2005). Range for velocity gradient was between 5-40 s^{-1}. Rotational speed was in the range of 0.3-3 rev min^{-1}. The coagulation water flows into flocculation basins, where flocculation is achieved in stages with varying velocity gradient. The following equation was used to estimate energy consumption for paddle wheel flocculators.

$$\mathrm{E}\ (kWh\ day^{-1}) = \frac{(\mathrm{G}^2)(\mu)(\mathrm{Q}_f)(\mathrm{t}_s)(t_m)(\mathrm{n}_f)}{\mathrm{f}}$$

Where, n_f = number of flocculation basins, Q_f =flow rate in each flocculation basin (m^3 $minute^{-1}$), t_s =detention time per stage (minute)

4.1.4 Filtration

Filtration basins were designed such that one basin was out of service to incorporate redundancy in the system. Rapid filtration that operates by gravity was selected as it is 100 times faster than slow sand filtration, and is accompanied by pretreatment process of coagulation as in this case. Later, it involves backwashing of collected materials.

Dual-media anthracite and sand filter was employed to trap the flocculated water, using rapid filtration process, and to provide a finished water quality of ≤ 0.3 NTU and 4 log removal of cryptosporidium. Filtration rate was taken as 14.5 m hr^{-1}, and effective size of anthracite was taken as 1 mm. Dual-media filter design was achieved by applying the design criteria provided by Reynold and Richards, (1996). Filter media consisted of 1.4 m of anthracite, and 0.25 m of sand, while the effective sizes were 1 mm, and 0.5 mm, respectively. Clean bed head loss was determined utilizing the Ergun equation (Crittenden et al. 2005). Typically rapid filtration process is designed with a net available head of 1.8-3.0 m. The filter is backwashed when the head loss exceeded the available head or limiting head, or increased turbidity is displayed in the filter effluent.

Energy consumers for the filters were the backwash pumps and air scour. The backwashing duration was assumed 9 minutes and backwash frequency of 24 hours was used based on the data obtained from the treatment plant. The energy consumption of pumps can be determined by using pump equation as discussed in Section 4.1.2. Air scour of the filter media was achieved for 4 minutes before the application of water backwash, and the design was based on the criteria provided by Hendricks, (2016) and Qasim (1998), whereas water backwash was designed using the criteria provided by Crittenden et al. (2005). Air blowers operate by developing pressure differential to move air between entrance and exit points. The power estimation for the air blower was made using the following equation (Qasim 1998).

$$P(kW) = \frac{wRT}{8.41e}\left[\left(\frac{P_2}{P_1}\right)^{0.283} - 1\right]$$

Where w=air mass flow (kg s^{-1}), R=Universal gas constant (kJ k^{-1} mole °K), T=air temperature at inlet (°K), P_1= absolute pressure at entrance (Pascal), P_2 =absolute pressure at exit (Pascal), e= efficiency=0.8, n= (k-1) k^{-1}=0.283 for air, and 8.41 is constant for air (kg k^{-1} mole)

4.1.5 Sedimentation

Sedimentation is the process during which suspended particles settle under gravity and form sediments or sludge. After the water is coagulated and flocculated, it moves into the sedimentation basins so that heavier flocs settle out of suspension.

Compared to conventional gravity sedimentation, parallel plate settlers provide enhanced solids removal capabilities in a smaller area. The settlers also improve the ability of the sedimentation process to perform well during periods of extremely high solid loadings to the plant. In the selected DWTP, six parallel plate sellers were provided, which were designed based on the criteria provided by Crittenden et al. (2005), Hendricks, (2016), and Kawamura (1991). Energy consumer for parallel plate settlers were sludge transfer pumps. Brake horsepower for sludge transfer pumps can be estimated using pump equation as discussed in Section 4.1.2

4.1.6 Chlorination

Disinfection can be accomplished through chlorination, ultra-violet radiation treatment, or ozonation. For the treatment plant, filtered water was disinfected through chlorination. Application of chlorine can take place as a gas or in a liquid form. Chlorination design was achieved using the design criteria established by USEPA. Other studies used in the design included Lauer et al., (2009), Lawlor & Singer, (1993), Lee & Lin, (2007). Sodium hypochloride (NaOCl) was the chemical used to accomplish disinfection, and was applied in liquid form. Surface water treatment rule was applied for 4 log inactivation of viruses and 3 log inactivation of giardia. Minimum one-hour detention at average design flow or 30 min detention at peak hourly flow was used, whichever was greater. Energy consumers for chlorination process were the metering pumps; the energy consumption can be determined using pump equation as discussed in Section 4.1.2

4.4.2 System Advisor Model

Design and performance analysis of solar PV was achieved using System Advisor Model, developed by National Renewable Energy Laboratory in 2005, and released for public use in 2007 (Gilman et al., 2008). SAM is a performance and cost-modeling tool, and facilitates in decision making for renewables of solar, wind, geothermal and biomass combustion.

Various studies have used SAM for analyzing solar technologies (Malagueta et al., 2014), particularly photovoltaics (Good and Johnson, 2016; Sweeney et al., 2016; Song and Choi 2015). Song and Choi, (2015) utilized SAM to generate hourly performance simulations for the validation of their solar PV design. Solar PV was used to generate power for the aerators, utilized for the treatment of acid mine drainage at Hwangji Youchang facility, located in Korea. The 30.1 kW PV system, using a factor of safety of 5, resulted in the electricity production of 3016 kWh month^{-1}, to meet the 342.39 kWh month^{-1} electricity demand (Song and Choi, 2015). Good and Johnson, (2016) utilized SAM to generate life cycle costs per kWh for utility-scale development of solar PV as well as for using solar PV to meet the electricity demands for residential and commercial sectors in the United States. Sweeney et al. (2016) employed SAM for analyzing life cycle energy production and associated costs of a solar PV system and solar water heater for a residential dwelling unit in Houston, Texas.

4.4.2.1 Technical Analysis

SAM evaluates energy performance and cost for grid-connected systems based on location, and system design parameters. Electric load of DWTP, electric rate, typical Meteorological Year (TMY3) data of the location as well as the parameters related to PV panels were the primary inputs for SAM. SAM facilitates in the design of the solar systems, as well as conducts financial feasibility of the project.

PV system was sized by SAM by using the inputs of desired array size, and a DC-to-AC ratio. This along with the parameters of selected module and inverter, required number of inverters and modules were determined. Nameplate capacity was determined as the product of module's maximum rated power and total number of modules. Some of the equations used to size solar PV are as follows:

$$M_{string} = \frac{V_{mppt-max} + V_{mppt-min}}{2V_{max}}$$

$$M_{parrallel} = \frac{C}{I_{pmax} M_{string}}$$

$$I_n = \frac{(M_n)(M_{mp})}{DC - AC\ Ratio\ (I_{map})}$$

$$M_n = M_{string} M_{parallel}$$

Where M_{string}= modules per string, $M_{parallel}$=module strings in parallel, $V_{mppt-max}$= maximum MPPT voltage, $V_{mppt-min}$= minimum MPPT voltage, V_{max}= maximum power voltage, C=array nameplate capacity (kW), I_{pmax}= module maximum power. I_n=number of inverters, M_{mp}= Module maximum power, I_{map}= Inverter maximum AC power, M_n=total number of modules

Battery storage was also provided, primarily to meet energy demands at nighttime since the treatment plant operated for 24 hours per day. SAM allows the analysis of three types of batteries: lead-acid, lithium-ion, and vanadium redox flow. For this study, lead-acid battery was used. Battery was assumed to be connected on the AC side. Battery bank size can be specified as either number of battery cells in series and battery strings in parallel, or it is estimated by SAM using the inputs of desired bank capacity and bank voltage.

$$B_{ns} = \frac{B_{dbv}}{B_{ncv}}$$

$$B_{nbv} = B_{ncv} * B_{ns}$$

$$B_{np} = \frac{B_{dbc}}{B_{nbv} * B_{cc}}$$

$$B_{nbc} = B_{ns} * B_{np} * B_{cc}$$

Where B_{ns}=number of battery cells in series, B_{dbv}= desired bank voltage, B_{ncv}= battery nominal cell voltage, B_{nbv}= nominal bank voltage, B_{np}=number of battery strings in parallel, B_{cc}= battery cell capacity, B_{nbc}= nominal bank capacity, B_{dbc}= desired bank capacity. Nominal cell voltage was manufacturer reported voltage (volt) of a single cell in a battery, which was used to size the battery storage. C-rate governed the charge and discharge rate of the battery. Max C-rate of charge and discharge of 0.12 per hour was used.

4.4.2.2 Financial Analysis

Economic performance was analyzed using SAM by employing the parameters of net present value (NPV), and levelized cost of electricity (LCOE). NPV for a system examines the difference between present value of revenues and costs. Positive NPV means that the present expenses incurred are predicted to provide a return greater than the initial investment. If NPV is negative then the cash inflows are predicted to be less than the cash outflows and the investment is not financially beneficial. LCOE was also estimated which is the present value of the life cycle cost of the PV system. Real LCOE is adjusted for inflation, whereas nominal LCOE is not. Net savings in \$ year^{-1}

are estimated by taking the difference between the costs for purchased electricity, with and without the solar system.

For this study, NPV was used as the primary metric to determine the financial feasibility of the PV system. This is because the analysis includes the input parameters of taxes and incentives, which may complicate the estimation of more simplistic metrics such as payback period. In addition, payback period is not recommended when investment is to be considered explicitly. NPV gives value to the size of investment while the metrics of LCOE and payback period do not (Short et al. 1995).

Various financial parameters were incorporated within the economic model of SAM. Some of the financial parameters used as an input are listed in Table 4.3 while others are discussed in the following sections. These parameters were based upon the review of published literature in the years 2016 and 2017 (Fu et al 2016; Kang & Rohatgi, 2016; Krupa & Harvey 2017; Lai & McCulloch 2017; Mundada et al 2016; Musi et al 2017; Reiter et al 2016). Analysis period of 25 years was used based upon the warranty period of the PV panels.

Table 4.3: Financial parameters utilized as inputs in System Advisor Model.

	Parameter	Unit	Value
Direct Cost	Module	$ Watt^{-1}	1.6
	Inverter	$ Watt^{-1}	5.0
	Battery Bank	$ kWh^{-1}	157.7
	Balance of equipment cost	$ Watt^{-1}	0.32
	Installation labor	$ Watt^{-1}	0.15
	Installer margin and overhead	$ Watt^{-1}	0.19
Indirect capital Cost	Permitting, environmental studies, grid interconnection	$ Watt^{-1}	0.02
	Engineering and developer overhead	$ Watt^{-1}	0.62
Tax Rates	Federal income tax rate	% year^{-1}	28.0
	State income tax rate	% year^{-1}	0.0

Net capital cost of the solar system was calculated by SAM, by subtracting cash incentives from total installed costs (sum of direct and indirect cost). Direct and indirect cost of the system is shown in Table 4.3 (Freecleansolar, 2017a; Wholesalesolar, 2017b; Wholesalesolar, 2017c). Annual costs incurred for the operation, maintenance and repairs of the solar system, after it has been installed, constitute as operation and maintenance (O&M) cost. A fixed annual amount of \$18 kW^{-1} $year^{-1}$ was specified, which increased each year based on inflation rate for this analysis. The income tax rate can be specified as a constant or variable value for each year. Any savings through the application of state or federal incentives are also taxable. Savings achieved due to the installation of solar system was not taxable; however, O&M costs were taxable. Salvage values were taken as 20% of installed costs (McCabe, 2011). Debt percentage, which is a fraction of the net capital costs, was specified as 100% and the debt payments were assumed constant. The loan period was also specified but it can vary from the analysis period. Principal amount is estimated by SAM as the product of total installed cost and debt percentage. Loan term of 25 years and interest rate of 3.5% were used as an input to SAM (Musi et al. 2017).

Within the analysis parameters, default inflation rate of 2.5% was used, which was the yearly mean consumer price index data between the years 1991 and 2012. The inflation rate was applied to system costs, additional costs listed on financial parameters page, electricity rates, and cash incentives. Real discount rate of 8% was used which is nominal discount rate minus inflation rate, and is used for the estimation of NPV and LCOE by SAM.

In SAM, yearly insurance cost and property tax cost is tax deductible for commercial projects and is a component of the annual operating costs. Insurance rate was taken as 0.25% of the installed costs (Reiter et al. 2016). For first year, insurance amount was a product of insurance rate and total installed cost, which is then increased by inflation rate of 2.5% for later years. Property tax amount is the product of property tax rate and assessed value of the property. Property tax rate was taken as zero to incorporate property tax exemption incentive.

Depreciation reduces federal and state taxable income. Sometimes the method used to estimate depreciation is dictated by the Federal Government or the state. Different depreciation methods are available. MACRS (Modified Accelerated Cost Recovery System) is a depreciation method to help recover capital costs and reduce tax liability, which was utilized for this analysis. Commercial solar PV is eligible to depreciate over a five year period (DSIRE, 2017), as determined by Internal Revenue Service at depreciation rates of 20%, 32%, 19.2%, 11.52%, 11.52%, and 5.76 % for year 1,2,3,4,5, and 6, respectively. The renewable energy system's taxable basis can be reduced by one-half of the investment tax credit of 30%, hence 85% of the taxable basis can be reduced. 50%, 40% and 30% bonus depreciation can be further applied for solar PV systems placed in service before the year 2018, during 2018 and during 2019, respectively. Qualifying solar systems are ones that claim the 30% ITC.

Sales tax amount was estimated as the product of sales tax % and direct cost. Since SAM incorporates sales tax amount as a part of total installed costs of the solar system, sales tax amount influences the estimates of depreciation, debt amount and debt interest payments, as well as debt interest payment deductible estimate from federal and state income tax. The sales tax is partly exempted based on state incentives, but was not incorporated in the analysis since state property tax exemption was incorporated in the analysis. Sales tax of 8.1% was used.

4.4.3 Land Area Requirements

Land area requirements for PV system were estimated by SAM by dividing the total module area with ground coverage ratio (GCR). Total module area can be estimated by taking the product of the area of a single PV module to number of modules required. GCR is the ratio of the side view diagonal length of one row to bottom length spacing between two rows (Doubleday et al. 2016). GCR value ranges between 0.01 and 0.99. GCR value close to zero implies PV arrays are spaced further apart compared to GCR value close to 1.

GCR of 0.3 was used for the analysis. The value was selected based on a self-shading analysis for PV modules, employing the criteria provided by Brownson, (2013) for tracking systems. Shading due to obstructions such as buildings or trees can also be incorporated in the shading analysis. Other than the reason of minimizing self-shading, spacing between the modules is required for access and maintenance work.

Land area availability for the development of solar PV was determined by estimating the available land-holdings of the treatment facility by using ArcGIS software.

4.4.4 Carbon Emissions

Carbon emissions were estimated by making use of the data provided in Table 4.2. State's electricity source distribution was used to estimate carbon emissions in the case of non-PV based design. Carbon emissions related to PV based design were subtracted from those of non-PV based design to determine net reduction in carbon emissions per kWh. Carbon emissions generated due to solar PV are those generated during transportation, construction and disposal phase, but during operation of a solar installation, there are negligible emissions (Nugent & Sovacool, 2014).

4.5 Scenarios Analyzed

The determination of energy consumption and the techno-economic feasibility using SAM was conducted for two main scenarios for the selected treatment plant. Scenario 1 (S-1) represented analysis for the DWTP including water distribution pumps whereas Scenario 2 (S-2) represented the analysis for DWTP without including the water distribution pumps. Analysis was conducted for both these scenarios, in standalone mode (with storage) and grid-connected mode (without storage). Further, the analysis was conducted for two geographical locations, southwest US where the plant is located, and US east coast.

4.5 Results and Discussion

4.5.1 DWTP Design and Energy Consumption

The results for the analysis are discussed as follows. Various unit processes involved in the treatment of water were designed, energy driving units for each unit operation were identified and energy consumption in the units of kWh day^{-1} and kWh m^{-3} was determined for each unit operation.

Raw river water flowed by gravity from Highland Canal, passing through bar screens and flowed by gravity through the rest of the plant. The bar screens were cleaned manually. Next the water flowed by gravity through the pre-sedimentation basins and the screening facility. For avoiding settling of suspended solids in the treatment plant piping, two pre-sedimentation tanks or raw water basins were provided. Surface loading rate of 380 m day^{-1} was used. The two pre-sedimentation basins were cleaned manually using wheel loaders. The basins were sized as 44.5mx10mx4m.

Next, the water flowed into the screening facility, which was designed to remove floatable solids from raw water. The fine-screen opening size was 9.53 mm, and each screen area was 1.4 m^2. This screen accomplished 90% of solid removal larger than 4.7 mm. The screens were cleaned using backwashing jets (551.6 kPa) for 15 minutes day^{-1}.

Screened raw water flowed into coagulation facility where in-line rapid mixers and jet-diffuser were used to flash-mix coagulant and coagulant aid polymer, respectively. Two in-line mixers were provided. Each 12.5 kW mixer was housed in a 1.5 m diameter pipe, and operated for 24 hours a day. Jet diffuser pump utilized a diffuser with a diameter of 0.01 m. The energy consumption was found to be 202.8 kWh day^{-1}.

Downstream of rapid-mixing, treated water flowed through six flocculation basins where the slow mixing of the coagulated water was achieved through paddle wheels. The detention time for the basins was 25 minute. Three stages, with velocity gradients of 70 s^{-1}, 50 s^{-1} and 30 s^{-1} were provided for each flocculation basin of volume 985.8 m^3.

Effluent from six flocculation basins flowed through submerged openings into six sedimentation basins. Peak hydraulic capacity of each basin was 15 MGD, and a volume of 1105.6 m^3. The flow pattern within the sedimentation basins was across and upward through packs of parallel plates (1.7mx0.75m). Spacing provided between the plates was 60 mm, inclined at an angle of 60 degrees. Reynolds number was determined to be <1000 to ensure laminar flow, while Froude number was $>10^{-5}$. Water collected in the troughs at the top of plate settlers that discharged the effluent to the sedimentation basin's effluent channel and flowed by gravity to the filters. Compared to conventional gravity sedimentation, the parallel plate settlers provided enhanced solids removal capabilities in a smaller basin area. The settlers also improved the ability of sedimentation process to perform well during periods of extremely high solid loadings to the plant.

Following the removal of most of the suspended solids in the sedimentation basins, water was filtered through twelve dual-media filters, including one filter for redundancy. Water entered the filter influent distribution channel from sedimentation basin, entered each filter and passed through the filter media and underdrain system to filter flume channel, and finally conveyed to finished water reservoir. Filtration rate of 14.5 m hr^{-1} was used. Area of each filter basin was 89 m^2. Clean bed head loss was determined to be 0.77m. Net available operating head for the DWTP was 3.0 m. The filter was backwashed when the head loss exceeded the available head or limiting head.

Filters were backwashed using both air and water. Air scour was provided to agitate the filter media for about 4 minutes, before backwashing the filters with water. Airflow rate of 1.4 m^3 sec^{-1} was used. The filters were backwashed every 24 hours, while filter-to-waste duration of 15 minutes was used. Backwash water supply was pumped from plant pump station to the filters by backwash water supply pumps. After the application of air scour, the filters were backwashed using water for about 9 minutes. Recovery was 97%.

Sodium hypochlorite was used to disinfect filtered water at the two finished water reservoirs, each having a volume of 9460 m^3. Surface water treatment rule was applied for 4 log inactivation of viruses and 1.5 log inactivation of giardia for a CT value of 165 mg l^{-1}-min at pH 8. Disinfection of cryptosporidium was achieved during filtration, hence was not included in the chlorination design. Contact time of 88 minutes was used. Residual chlorine concentration was 1.9 mg l^{-1}. Length to width ratio of 47:1 was used for the baffles (hence greater than 40:1 ratio recommended by USEPA).

Soda ash system was designed to prepare and convey soda ash solution to the rapid mixer (0.6 kW), designed for a velocity gradient of 1000 s^{-1} and detention time of 20 sec. Later soda ash feed pumps conveyed the slurry from the mixing tank to points of application at the finished water pump station where it was used to increase pH and alkalinity. Finally, the water was pumped to Hunter Creek, Northgate and Highland zones.

Plant's process wastewater generated during filtration and sedimentation was conveyed to decant basin and water recovery basins, respectively, via a 1.2 m pipeline. At these facilities, plant waste solids were concentrated and dewatered to recover water and to facilitate ultimate solids disposal. Backwash wastewater flowed by gravity from filters to decant basins for primary solids settling. Two decant basins were designed (37mx8mx4m) using the same design criteria of pre-sedimentation basins. After a short detention period of 30 min, decanted water was pumped from decant basin pump station to raw water junction box, where it was recycled through the plant. Decant basin settled solids were pumped by solids transfer pumps to water recovery basins for secondary solids settling. Two water recovery basins, received sedimentation basin solids, by gravity. These basins were designed using same criteria as pre-sedimentation tanks. Each basin was sized as 53mx8.5mx4m. The basins were designed for a surface loading rate of 375 m^3 m^{-2} day, and a detention time of 8 minutes.

Results for energy consumption estimations for the DWTP are shown in Table 4.4 and 4.5, and Figure 4.2 and 4.3. The energy consumption estimated by the current study was validated by comparing the estimated motor sizes to the plant motor sizes. As shown by Table 4.4 and 4.5, the values are in good agreement with each other.

The selected DWTP is unique concerning raw water intake. Raw river water flowed by gravity from Highland Canal into the DWTP; thus, no energy was utilized for water intake. Water distribution pumps consumed 158.2 Wh m^{-3} and were the largest consumers of electricity, utilizing about 95% of the total energy consumption, while the remaining 5% was utilized for the operation of the DWTP (Figure 4.2, Table 4.4-4.5). Backwashing jet pumps for screens were the smallest consumers of energy within the DWTP, consuming about 0.004 Wh m^{-3} (Figure 4.3). Overall, it was shown that coagulation and flocculation processes were the largest consumers of energy, consuming about 664 kWh day^{-1} (1.95 Wh m^{-3}), and 659 kWh day^{-1} (1.93 Wh m^{-3}), respectively (Figure 4.3, Table 4.4). The energy driving units for coagulation process consisted of metering pump and in-line mixer for coagulation addition and mixing, respectively, while a jet diffuser pump was utilized for polymer addition and mixing. Eighteen paddle wheels were employed for the flocculation process. Both coagulation and flocculation processes partook about 50% of the total energy consumption of the DWTP. Pumping operations within the DWTP utilized about 54% of the total energy consumption. The processes of chlorination for disinfection, soda ash injection to raise pH, and automatic cleaning of screens using backwashing jets consumed approximately 4% of the total energy. Mixing operations during coagulation, flocculation and soda ash slurry mixing utilized about 40% of the total energy consumption of the DWTP.

Further, unit-process based quantitative assessment of energy intensities as computed in this study may help compare and improve performance of treatment plants. Plant of similar capacities may not be utilizing similar paths of treatment. Hence, the energy consumption maybe recomputed based on the unit processes being utilized by the plants, resulting in a more fair energy performance comparison (Figure 4.3). The unit-process based quantitative assessment of energy intensities may help compare performance of different plants more accurately, and may identify opportunities for improvement.

For scenario S-1, total energy consumption was 56.3 MWh day^{-1} (165.3 Wh m^{-3}) for DWTP including water distribution pumps, whereas energy consumption for scenario S-2 i.e. for the DWTP excluding water distribution pumps was 2661 kWh day^{-1} (7.8 Wh m^{-3}).

Sensitivity analysis was performed for the energy consumption estimates related to pumping operation for the treatment plant. Wire-to-electric efficiencies of the pumps were increased by 5% and 10%, which resulted in 2.6% (2.59 MWh day^{-1}) and 4.9% (2.53 MWh day^{-1}) decrease in the total energy consumption (2.66 MWh day^{-1}) of the water treatment units respectively. Whereas decreasing wire-to water efficiencies by 5% (2.74 MWh day^{-1}) and 10% (2.82 MWh day^{-1}) resulted in increased total energy consumption by 2.8% and 6%.

Soshinskaya et al. (2014) determined energy consumption for a large-scale water treatment plant in Netherland and reported total energy consumption of 172 Wh m^{-3} for the treatment plant including intake pumps and water distribution pumps. Pirnie and Yonkin, (2008) reported that in the U.S. average electricity use for water supply systems including water pumping, treatment and distribution amounted to about 369.8 Wh m^{-3}, whereas for that of New York State was about 186.2 Wh m^{-3}.

Table 4.4: Results for the estimation of energy consumption for the various unit processes of the drinking water treatment facility.

s.no.	Unit Process	Sub-Processes	Energy Driving Unit	Plant Motor Size (hp)	Estimated Motor Size (hp)	Motor Size (kWh day^{-1})	Efficiency (%)
1.	Automatic Screens	Screen Cleaning	Backwashing Jet Pump	3	3.4	1.3	49
2.	Coagulation	Coagulant addition	Metering pump	N/A	5	85.8	76
		Polymer addition	Jet Diffuser Pump	7.5	7.25	202.8	64
		Flash Mixing	Static Mixer	15	16.8	375.2	80
3.	Flocculation	Slow Mixing	Paddle Wheels	5	4.9	658.8	80
4.	Sedimentation		Sludge transfer pumps	7.7	7.5	411	72
5.	Filtration		Air Scour	250	247.6	169.2	80
			Backwash water transfer pumps	200	199.6	272.9	77
6.	Water Recovery Basins		Water Transfer Pumps	50	49	292.4	76
7.	Decant Basin		Water Transfer Pumps	30	29.2	65.4	76
			Sludge transfer pumps	7.5	7.7	17.2	72
8.	Chlorination	Chlorine addition	Metering pumps	N/A	3	52	76
9.	Soda Ash System		Soda Ash Mixer	0.75	0.75	16.7	80
			Slurry Feed Pump	N/A	1.7	40.7	72
					Total	2661.4	

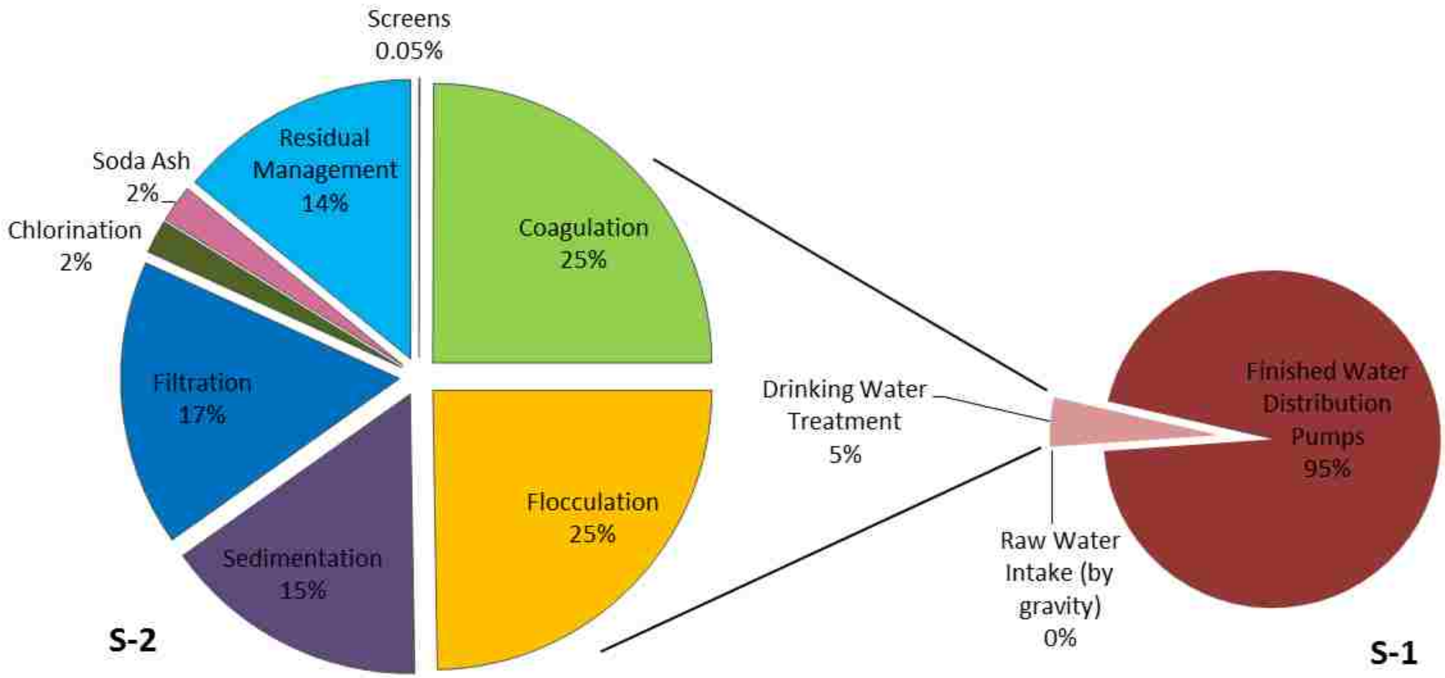
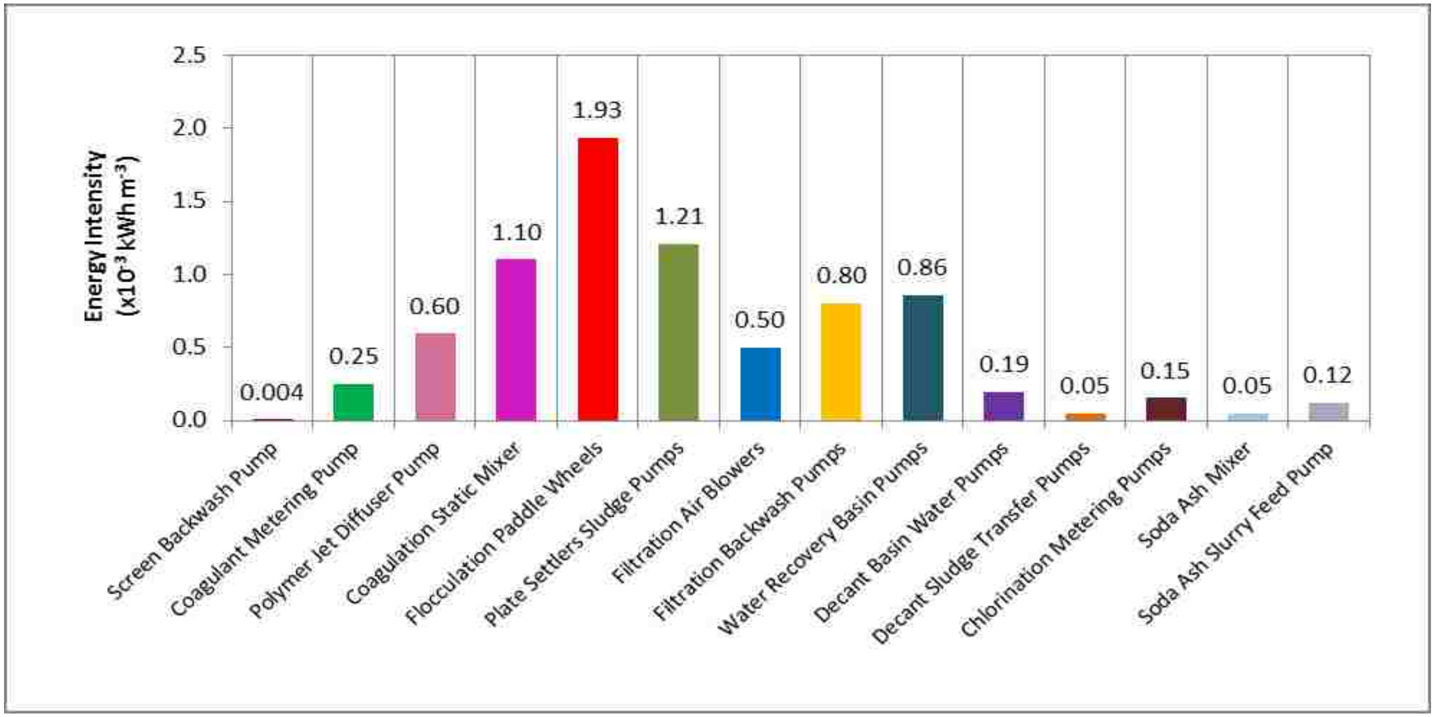


Figure 4.2: Energy consumption by percentage for water intake, water treatment units and finished water distribution pumps for scenario S-1 (energy consumption of water treatment facility including distribution pumps) and S-2 (energy consumption of water treatment facility excluding distribution pumps).

Table 4.5: Results for estimation of energy consumption for energy driving units of finished water pumping.

	Energy Driving Units	Plant Motor Size (hp)	Estimated Motor Size (hp)	Motor Size (MWh day^{-1})	Efficiency (%)
Finished Water Pumping	Northgate Pump	500	496.5	8.9	80
	Highland Pump	400	404.7	7.2	70
		400	404.7	7.2	70
	Hunter Creek Pump	250	248.1	4.4	80
		460	421.1	7.8	80
		500	509.6	9.1	80
		500	509.6	9.1	80
				Total 53.9	



Coagulation		**Flocculation**	**Sedimentation**	**Filtration**		**Chlorination**	**Soda ash system**	**Residual Management**	**Energy Intensity**
Jet diffuser pump	**Static mixer**	**Paddle wheel**		**Air scour**	**Backwash pumps**	**Metering pumps**			
0.6	**1.1**	**1.9**	**1.2**	**0.5**	**0.8**	**0.15**	**0.17**	**1.1**	**7.8**
√	√	√	-	√	√	√	√	√	**6.6**
-	√	√	-	√	√	√	√	√	**6.0**

Figure 4.3: Results generated for the energy intensity of various unit processes of the drinking water treatment facility.

4.5.2 System Advisor Model

Design of solar PV and the economic analysis was achieved using System Advisor Model.

Electricity rates and electric load were specified as inputs. The energy consumption determined in Section 5.2 was used as an electric load input for sizing solar PV. Total energy consumption including water distribution pumps was 56.3 MWh day^{-1} (S-1), whereas energy consumption for the DWTP only was 2661 kWh day^{-1} (S-2). This value represented energy consumption of the treatment plant determined for the maximum flow anticipated for the design life of the treatment plant. Hence, the estimate is representative of the worst-case scenario for the DWTP, and was assumed to be constant throughout the year. Other parameters chosen were also reflective of the extreme conditions.

Electricity generation by the PV system meets the facility's electrical load that would otherwise be met by electricity from the grid, and hence reduces the electric bill. Time of use (TOU) electricity rates for large general service were applied that mainly consisted of energy charges, demand charges, fixed monthly charges and facilities charge. Summer months comprised of July, August and September, whereas the remaining months were treated as winter months. Electricity rates were different for summer and winter months. Rate charges were also based upon voltage levels categorized as secondary ($\leq$600V), primary (levels between 600-25000V) and high voltage transmission (>25000V). Rates for secondary voltage levels were applied for the DWTP.

Net metering allows the owners of solar facilities to be credited for electricity additions made to the grid by the solar system. For the selected location, the electric utility allowed net metering for solar systems with capacities upto one MW for residential facilities and commercial facilities with monthly energy consumption less than 10 MWh and demand less than 50 kW. Hence, the DWTP did not qualify for net metering.

The PV system was 2-axis tracking and consisted of mono-crystalline silicone module assumed to be ground mounted. 2-axis tracking system allows higher energy output compared to single-axis trackers or fixed systems. The module type selected was Helio USA 7T2 305, with an efficiency of 15.6%, maximum power rating of 304.9 W and having 72 number of cells. Inverters were used to convert the direct current output of the solar modules into alternating current, so that the generated electricity can be utilized by the DWTP or the excess generation can be utilized by the electric grid. The inverter type selected was Fronius Symo 10.0 240V, with an efficiency of 96%, and maximum power rating of 10.3 kW. Parameters used for sizing solar PV, related to PV module, inverter, battery storage as well as various losses incorporated are shown in Table 4.6 and 4.7.

The DWTP operated for 24 hours in a day, hence to meet the night-time energy requirements, as well to ensure a balanced supply of energy, battery storage was provided. Battery type chosen was lead acid flooded. Cell capacity of the battery was 1284 Ah, and nominal voltage was 2 V. Battery bank parameters used as an input are shown in Table 4.7. SAM utilized a lifetime model that considered battery charge cycles as the main reason for capacity degradation. Capacity degradation was simulated as a function of depth of discharge and number of charge cycles, where depth of discharge described the state of battery's remaining charge. The capacity losses were incorporated into the maximum battery capacity after each charge cycle had elapsed. SAM does not incorporate thermal behavior of battery into the lifetime model; hence, it was assumed that battery was stored in an air-conditioned room, at constant temperature. Minimum and maximum state of charge for the battery affects battery lifetime, hence minimum discharge and maximum charge limits were set as

10% and 95 % respectively, based on battery type selected. Direct costs include equipment and labor costs as shown in Table 4.3, applied for year zero only in the economic analysis. Contingency percentage of 4% incorporated costs incurred due to unforeseen events. Indirect costs as shown by Table 4.3, incorporated engineering, permitting and grid interconnection costs, not directly related to PV system installation and equipment. If land required for installation of PV system needs to be purchased, the land cost can be incorporated in the financial model. This study assumed that the existing empty land acreage of the treatment plant would be utilized for the installation of PV system. Hence, land purchase costs were taken as zero. Salvage values were taken as 20% of installed costs (McCabe, 2011). Analysis period of 25 years was used.

Results of the analysis conducted by SAM are shown in Table 4.8, Figure 4.4 and 4.5. When analyzing for DWTP including water distribution pumps (S-1), nameplate capacity of the solar PV system was 11.5 MW, a battery bank capacity of 1700 MWh, with a net capital cost of $329 million, and a NPV of $5.4 million (Figure 4.4, Table 4.8). Comparatively, when sizing for DWTP excluding distribution pumps (S-2), the capacity of the solar system was 500 kW, battery bank capacity of 75 MWh with a net capital cost of $14.5 million and NPV of 0.24 million (Figure 4.4, Table 4.8). For reliable supply of electricity throughout the 24 hours duration of the day, large battery storage, need to be provided as shown by the results.

Table 4.6: Photovoltaic system design parameters utilized as inputs in System Advisor Model.

	Parameter	Unit	Value
Module	Module Name	-	Helio USA 7T2 305
	Module Area	m^2	1.952
	Module Material	-	Mono C-Si
	Nominal Efficiency	%	15.6
	Maximum Power Pmp	Watt	305
	Maximum Power Voltage Vmp	Volt	36.7
	Maximum Power Current Imp	Ampere	8.3
	Open Circuit Voltage Voc	Volt	45.1
	Short Circuit Voltage Isc	Ampere	8.9
Inverter	Inverter Name	-	Fronius-Symo 10.0-3 240V
	Weighted Efficiency	%	96.5
	Maximum AC Power	Watt	9995
	Maximum DC Power	Watt	10359
	Nominal AC Voltage	Volt	240
	Maximum DC Voltage	Volt	600
	Maximum DC Current	Ampere	41.5
	Minimum MPPT DC voltage	Volt	300
	Nominal DC Voltage	Volt	371.6
	Maximum MPPT DC Voltage	Volt	500
Losses	Average Annual Soiling Loss	%	5
	Connection Losses	%	0.5
	DC wiring Losses	%	2
	AC Wiring Losses	%	1
	System Performance Degradation Rate	%	0.5

Table 4.7: Battery Parameters utilized as inputs in System Advisor Model.

	Parameter	Unit	Value
Battery Type	Name	-	Lead Acid Flooded
Voltage Properties	Cell nominal voltage	Volt	2
	Internal Resistance	Ohm	0.1
	C-rate of discharge Curve		0.05
	Fully Charged Cell Voltage	Volt	2.2
	Exponential Zone Cell Voltage	Volt	2.06
	Nominal Zone Cell Voltage	Volt	2.03
	Charged Removed at Exponential Point	%	0.25
	Charge Removed at Nominal Point	%	90
Current and Capacity	Cell Capacity	Ah	1284
	Max C-rate of Charge	$Hour^{-1}$	0.12
	Max C-rate of Discharge	$Hour^{-1}$	0.12
Charge Limit and Priority	Minimum State of Charge	%	10
	Maximum State of Charge	%	95
	Minimum Time at Charge State	min	10

Table 4.8: Results for technical and financial analysis of solar PV system using System Advisor Model, for scenarios S-1(PV system with battery storage for 24-hour operation per day to support 100% of electric load) and S-2 (PV system with battery storage for 24-hour operation per day to support 5% of electric load related to water treatment units i.e. excluding distribution pumps).

	Parameter	Unit	S-1 (100% of electric load)	S-1 (80% of electric load)	S-1 (60% of electric load)	S-1 (40% of electric load)	S-1 (20% of electric load)	S-2 (5% of electric load)
Module	Nameplate Capacity	kW	11,500	8000	5900	3,900	2,000	500
	Number of Modules	-	37,710	26,230	19,340	12,780	6,550	1,630
	Modules per String	-	10	10	10	10	10	10
	Strings in parallel	-	3771	2,623	1,934	1,278	655	163
	Total Module Area	x 10^3 m²	73.61	51.2	37.8	25	12.8	3.18
	String Voc	Volt	451	451	451	451	451	451
	String Vmp	Volt	366.5	366.5	366.5	366.5	366.5	366.5
Inverter	Total Capacity	kWac	9,585.2	6,666.7	4,917.5	3248.4	1,730	410
	Number of inverters	-	959	667	492	325	173	41
	Maximum DC Voltage	Volt	600	600	600	600	600	600
	Minimum MPPT Voltage	Volt	300	300	300	300	300	300
	Maximum MPPT Voltage	Volt	500	500	500	500	500	500
	DC to AC Ratio	-	1.2	1.2	1.2	1.2	1.2	1.2
	Total Land Area	x 10^3 m²	245.2	170.8	125.9	83	42.5	10.5
Battery	Nominal Bank Capacity	MWh	1,700	1250	915	610	310.5	75
	Nominal Bank Voltage	Volt	350	350	350	350	350	350
	Cell in Series	-	175	175	175	175	175	175
	Strings in Parallel	-	3783	2782	2,037	1,358	691	167
	Battery efficiency	%	92.7	92.7	92.7	92.7	92.7	92.7
Financial Metrics	Net Present Value	$ million	5.4	3.98	2.97	1.97	0.99	0.24
	Levelized cost of electricity (nominal)	Cents kWh^{-1}	2.61	2.71	2.7	2.71	2.7	2.65
	Levelized cost of electricity (real)	Cents kWh^{-1}	2.12	2.20	2.19	2.2	2.19	2.15
	Net Capital Cost	$ million	329.3	240.6	176.3	117.4	59.8	14.5
	Electricity bill without system (year 1)	$ million	1.6	1.3	0.96	0.64	NA	0.08
	Electricity bill with system (year 1)	$	6,444	6,444	6,444	6,444	6,444	6,444

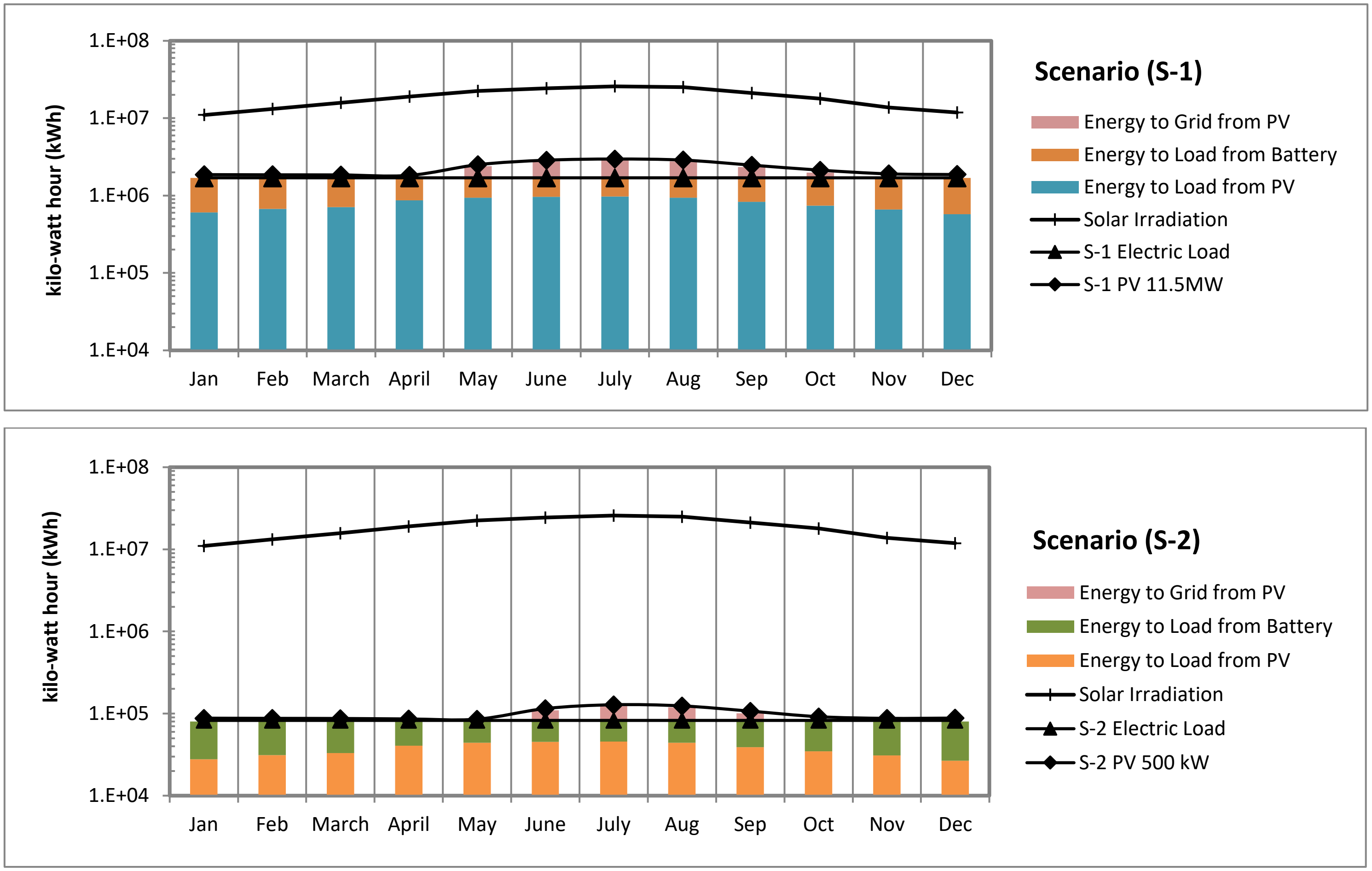


Figure 4.4: Inputs of electric load and solar irradiation and outputs for photovoltaic (PV) energy generation for the drinking water treatment facility for scenario S-1 (energy consumption of water treatment facility including distribution pumps) and scenario S-2 (energy consumption of water treatment facility excluding distribution pumps).

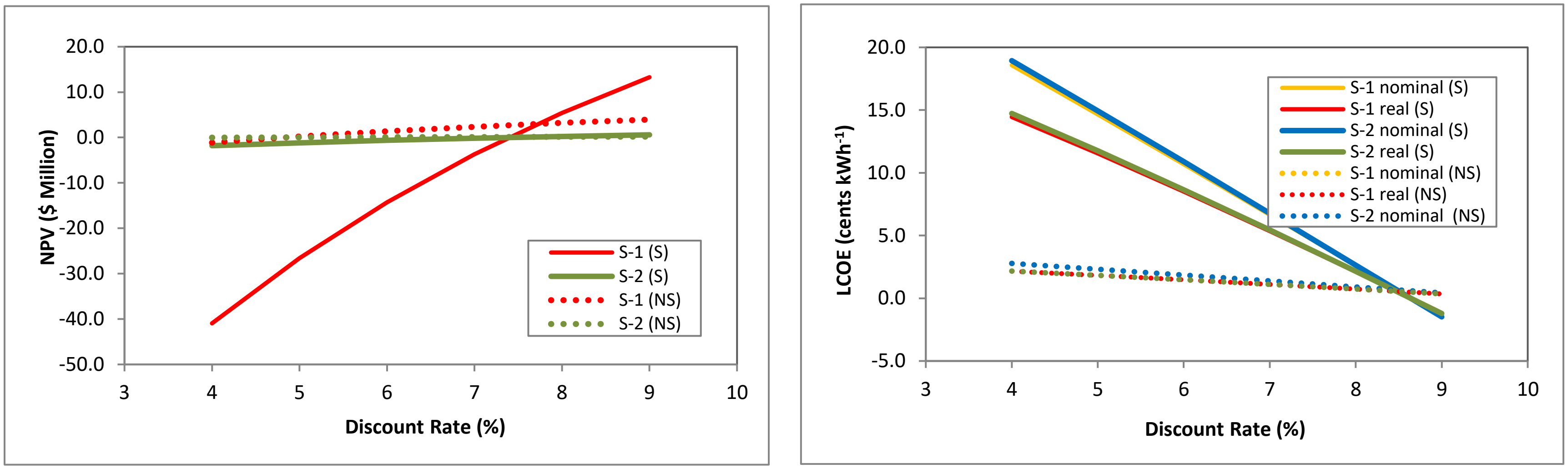


Figure 4.5: Sensitivity analysis performed to determine the influence of real discount rate (4-9%) on the financial metrics of net present value (NPV) and levelized cost of electricity (LCOE) real and nominal for scenario S-1 (energy consumption including distribution pumps) and scenario S-2 (energy consumption excluding distribution pumps) with storage (S) and with no storage (NS).

Even though the NPV was positive for the scenario S-1 and S-2, the value is small compared to the net capital costs incurred. Higher NPV is better than a lower NPV. It was seen that the battery storage comprised over 80% of the capital costs of the PV system. A scenario was simulated by decreasing the battery prices from \$157.7 kWh^{-1} to \$15.77 kWh^{-1}. This resulted in net capital costs of \$68.5 million, NPV of \$ 8.75 million, nominal LCOE of 1.1 cents kWh^{-1}, and real LCOE of 0.89 cents kWh^{-1} for scenario S-1. For scenario S-2, the results showed a NPV of \$0.4 million, and net capital costs of \$3 million. Nominal and real LCOE were estimated as 0.11 cents kWh^{-1} and 0.9 cents kWh^{-1}, respectively. The results show that for solar energy to become an attractive prospect for investors, and for a reliable supply of electricity throughout the 24 hours in a day using PV systems, prices for battery storage must decrease substantially. As seen by Table 4.8, there is a yearly electricity bill of \$6,444 for both the scenarios of S-1, and S-2. Since the system is grid-connected which was used as a backup generation for the treatment plant, these are the fixed yearly costs for grid connection.

PV system for scenario S-1 has the potential to offset 100% of the energy consumption of the plant and hence can act as a standalone system. However, because of high capital costs, it may be difficult to find financial investment for the PV project. Since initial cost for scenario S-1 was very high, additional scenarios were also examined (Table 4.8). As shown by Table 4.8, if only 20% of the energy consumption was offset utilizing solar PV, the capacity of the PV system was found to be 2 MW, whereas the capacity of the battery storage was found to be 310 MWh, with net capital costs of \$40 million.

Scenario S-1 and S-2 were also analyzed without incorporating battery storage and assuming that all other parameters remain the same. In this case, PV system would rely on grid-connection to meet the energy requirements for 24-hour operation of the plant. It was determined that for scenario S-1 and S-2, PV system without storage has the potential to offset 47% (11.5 MW system, net capital costs $40 million, NPV $3.2 million, real LCOE 0.7 cents kWh^{-1}), and 2.2% (500 kW system, net capital costs $1.7 million, NPV $0.16 million, real LCOE 0.7 cents kWh^{-1}) of the electric load, respectively. It can be seen that the costs incurred when battery storage was not incorporated were much lower, compared to when storage was provided. The results for PV systems for S-1 and S-2 when not incorporating battery storage are for comparison purposes, to reflect the effect of battery storage on cost and performance of the PV system.

A hypothetical scenario was examined by changing the location of the treatment plant to the US east coast. The location selected was White Plains, New York having direct insolation levels of 3.5 kWh/m^2/day compared to 6.3 kWh/m^2/day for the southwestern site. Financial parameters were not changed except sales tax rate for Westchester County where White Plains city is situated, which was taken as 4.375% and state income tax rate, which was taken as 8.82% for New York. The incentives incorporated were 30% ITC and 100% state sales tax exemption (DSIRE, 2017). The system did not qualify for other incentives. Property tax rate of 2% was used. The electric rate input utilized, downloaded from SAM database for electric rates, was based upon the rates of New York Power Authority for large general service.

The results showed that for S-1, the 11.5 MW PV system with 1700 MWh battery capacity was able to offset 100% of the 56.3 MWh day^{-1} electric load analyzed when sited in the southwestern location (scenario S-1, Table 4.8); however the same system when located in White Plains, New York was able to offset 92% of the total load analyzed. The battery storage was able to offset 53% of the load while the modules were able to support 39% of the load apart from charging the battery as well. The system size was changed to evaluate if it was possible to offset 100% of the load. It was determined that a 17 MW PV system using battery storage capacity of 2000 MWh was able to offset 100% of the 56.3 MWh day^{-1} electric load, for White Plains, New York location, however it was not economically feasible. The NPV was negative \$16.5 million, with LCOE value of 11.2 cents kWh^{-1}, while the net capital costs increased by \$56.7 million

The results showed that for S-2, the 500 kW PV system with 75 MWh battery capacity was able to offset 100% of the 2661 kWh day^{-1} electric load analyzed when sited in the southwestern location (scenario S-1, Table 4.8); however the same system when located in White Plains, New York was able to offset 85% of the total load analyzed. 47% of the load offset was achieved using battery storage. It was further determined that a 850 kW PV system (42% of load offset apart from charging the batteries) using battery storage capacity of 82 MWh (58% of load offset) was able to offset 100% of the 2661 MWh day^{-1} electric load, for White Plains, New York location, however it was not economically feasible. The NPV was negative \$0.67 million, with LCOE value of 9.6 cents kWh^{-1}, while the net capital costs increased by \$1.9 million.

Sensitivity analysis for the financial parameters that were changed when analyzing for the southwestern US and New York location, property tax rates were shown to have the largest effect. For New York location, property tax rate when changed from 2% to 1.2% would render the PV system financially feasible for S-1 (NPV of \$1 million and LCOE value of 3.7 cents kWh^{-1}) and S-2 (NPV of \$0.07 million and LCOE value of 3.3 cents kWh^{-1}). Property tax rate may vary depending upon location of the property. A property tax exemption or partial property rate incentives have the potential of greatly promoting the development of solar facilities in the state.

Sensitivity analysis was also performed for various financial parameters for the solar system sited at the southwest location for S-1 and S-2. As shown by the Figure 4.5, discount rate of 7% or less resulted in negative NPV. For the current study, debt percentage of 100% was used. Debt percentage of 96 % or less rendered a negative NPV and higher LCOE values. Reducing the loan term decreases the NPV and increases LCOE values. Using loan term of 23 years or less, or loan interest rates of 4% or higher, resulted in a negative NPV. For the current study, inflation rate of 2.5% was used. Using inflation rate of 1.9% or less resulted in a negative NPV. It can be seen that for this particular study, the viability of the project is sensitive to the changes in discount rate, inflation rate, debt percentage, loan interest rates and loan term. For the same PV system for S-1, and S-2, if battery storage is not provided, debt% of 85% or less, loan term of 18 years or less, discount rate of 4% or less (Figure 4.5), interest rate of 6% or higher, and inflation rate of zero or less rendered a negative NPV and higher LCOE values.

Okoye & Oranekwu-Okoye, (2017) determined the economic feasibility of using solar PV to fulfill the electricity needs of a rural community consisting of 300 homes, located in Gusau, Nigeria. The study found that the solar PV was highly sensitive to changes in electricity rates and inflation rates but slightly sensitive to changes in loan term and loan interest rate. Changes in year-round insolation levels due to change in location may also significantly alter the energy output of PV systems and thus the results of financial analysis as well (Al-Sharafi et al. 2017; Okoye & Oranekwu-Okoye, 2017). Al-Sharafi et al. (2017) conducted a techno-economic assessment of using solar and wind energy with storage systems for locations in Kingdom of Saudi Arabia (KSA), Canada and Australia. The study determined the cost of electricity to be lowest for Yanbu area in KSA as 0.609 $ kWh^{-1}. Further, the study determined the renewable potential of KSA to be better than the selected locations in Canada and Australia due to higher year-round levels of solar irradiance.

Financial feasibility heavily relies on government incentives. Two incentives were applied, federal investment tax incentive and the state property tax exemption incentive for this study for the southwest location resulting in nominal and real LOCE values of 2.61 and 2.12 cents kWh^{-1}, respectively for scenario S-1, and 2.65 and 2.15 cents kWh^{-1}, respectively for scenario S-2. If either of these incentives were removed from the analysis, the development of solar PV would no longer be economically feasible, resulting in a negative NPV and increased LCOE values. Fu et al. (2017) reported LCOE values for commercial PV systems in the U.S. in the range of 9-12 cents kWh^{-1} when not incorporating federal ITC, and in the range of 6-8 cents kWh^{-1}, when incorporating it. For the current study, when the 30% ITC was not incorporated, NPV became negative, while the nominal and real LCOE values were estimated as \$0.38 kWh^{-1} and \$0.31 kWh^{-1} respectively, for scenario S-1, and \$0.39 kWh^{-1} and \$0.32 kWh^{-1} for scenario S-2. Hence, grid-parity was not achieved.

The largest portion of cost associated with the PV system was that of the battery storage, comprising over 80% of the PV system costs. Successful cost recovery of the solar PV system with battery storage during the lifetime of the PV system requires application of novel approaches for production of low-cost battery storage systems (Lewis, 2007). Reduction in battery prices can greatly promote the role of solar PV systems as a viable and competitive source of electricity generation for the 24-hour duration of the day.

Based on renewable portfolio standard (RPS) for the state, 25% of the electricity generation by the year 2025 must be achieved by using renewables (DSIRE, 2017). Portfolio energy credits earned due to the deployment of solar PV at the treatment plants can assist in meeting RPS goals. Incorporating net metering rates will improve the financial feasibility of the project, but the selected DWTP did not qualify for application of net metering rate. It was encouraging to note that even though net metering was not incorporated, PV system was still found to be economically feasible with positive NPV. Nevertheless, less stringent policies regarding net metering/ feed-in-tariffs can help encourage investments for the development and promotion of solar energy.

Incorporating renewables into the existing water infrastructure assists in reducing the dependency of water facilities on the traditional energy sources, thus generating reduced emissions. This helps in making water facilities energy independent, which will help achieve cost savings in the long run. Policy makers for water and energy need to participate in collaborative planning, and implement policies that provide incentives to existing and future water treatment facilities for using renewables to offset energy requirements.

García-Vaquero et al. (2014) compared the performance of a conventional DWTP and a wind-solar-powered nano-filtration pilot plant located in Spain. The study concluded that the application of nano-filtration process resulted in higher quality water, and usage of renewables, not only assisted in making an energy-intensive process sustainable, but also helped in making the water treatment process more efficient. Soshinskaya et al. (2014) explored the potential of using wind and solar energy for a water treatment plant located in Netherland. The study found that about 70-96% of energy independence can be achieved by using 8 MW wind turbines and 5.6 MW solar panels, but due to high costs for large battery storage, 100% energy independence could not be achieved. Solar energy was used in conjunction with wind energy, because the site possessed large but erratic wind potential while solar energy using photovoltaics provided a more balanced supply. Halder, (2016) determined solar PV to be economically feasible for meeting the electricity needs of two villages located in Bangladesh.

4.5.3 Land Area Requirements

The land coverage of the PV system for the DWTP (S-2) was 0.01 km^2 and when sizing for water distribution pumps as well (S-1) was 0.25 km^2 (Table 4.8). The empty real estate acreage of the DWTP was about 0.4 km^2, estimated using ArcGIS. Hence, it can be seen that ample land area was available for development of solar PV, and additional costs need not incur for purpose of purchasing land for solar development. Moreover, ample empty land area is available near the DWTP that can be acquired for the installation of PV.

Noorollahi et al. (2016) determined that about 15% of the total land area of Iran provided excellent conditions for solar installations. Anwarzai & Nagasaka, (2017) determined optimal sites in Afghanistan for the development of wind and solar energy systems, resulting in potential generations of 0.34 million GWh per year and 0.15 million GWh per year, respectively.

4.5.4 Carbon Emissions

Net reduction in carbon emissions due to PV-based design was found to be 9500 metric tons CO_2eq $year^{-1}$ for DWTP (S-1), which is equivalent to emissions due to 2000 passenger cars driven for one year, or electricity consumption of 1400 homes for one year, or carbon sequestration due to 11,000 acres of U.S forests in one year. For S-2, net reduction in carbon emissions was found to be 450 metric tons CO_2eq $year^{-1}$, which is equivalent to emissions due to 95 passenger cars driven for one year, emissions due to electricity consumption of 67 homes for one year, or carbon sequestration due to 530 acres of U.S forests in one year. For S-1, without battery storage, net reduction in carbon emissions was found to be 4400 metric tons CO_2eq year^{-1}, which is equivalent to emissions due to 900 passenger cars driven for one year, emissions due to electricity consumption of 660 homes for one year, or carbon sequestration due to 5,200 acres of U.S forests in one year. For S-2, without battery storage, net reduction in carbon emissions was found to be 240 metric tons CO_2eq year^{-1}, which is equivalent to emissions due to 50 passenger cars driven for one year, emissions due to electricity consumption of 35 homes for one year, or carbon sequestration due to 280 acres of U.S forests in one year. The equivalencies were calculated using USEPA GHG Equivalencies Calculator (USEPA, 2017).

Burtt & Dargusch, (2015) determined reduction in carbon emissions due to residential installations of solar PV in Australia and determined it to be 3.7 million ton CO_2eq in the year 2013, and 8 million ton CO_2eq in the year 2020. Oliveira et al (2017) estimated GHG reduction of 1.7 ton year^{-1} for a zero energy solar home in São Paulo, Brazil. MacDonald et al. (2017) developed a simulation model incorporating estimated future costs for renewables of wind and solar and determined 80% reduction in carbon emissions by the year 2030 relative to the levels of the year 1990, without any rise in LCOE.

The development of solar PV for the scenarios S-1, and S-2, was found to be economically feasible as net present value was found to be positive. In addition, the gains achieved in public health and environmental impacts due to reduction in carbon emissions, makes the development of solar PV a good investment (Abrar-ul-Haq et al 2017, Buonocore et al 2016; Haines et al 2009; Shindell et al. 2016).

4.6 Conclusion

The objective of this study was to utilize solar PV to meet the energy demands of an existing 90 MGD DWTP by (a) determining the energy consumption of each unit operation of the treatment plant, (b) sizing the DWTP for solar PV based on available land holdings and economic feasibility and (c) determining the net reduction in carbon emissions due to solar PV development. The analysis was conducted for scenario S-1 (100% of electric load), scenario S-2 (5% of electric load i.e. excluding water distribution pumps), in standalone mode (with battery storage) and grid-connected mode (without storage). It was found that utilizing solar PV to offset the energy consumption of a 90 MGD existing DWTP was technically and economically feasible.

The study evaluated the energy consumption of the unit processes of the DWTP, and determined the following:

- For scenario S-1, total energy consumption was 56.3 MWh day^{-1} (165.3 Wh m^{-3}) for DWTP including water distribution pumps, whereas energy consumption for S-2 i.e. for the DWTP excluding water distribution pumps was 2661 kWh day^{-1} (7.8 Wh m^{-3}).
- For S-1, water distribution pumps utilized 95% of the total energy consumption of the DWTP, whereas the water treatment only operations (S-2) utilized the remaining 5% of the energy consumption. For S-2, overall, it was shown that coagulation and flocculation processes were the largest consumers of energy, each consuming about 25% of the total energy consumption of the DWTP. Pumping operations utilized about 54% and mixing operations utilized about 40% of the total energy consumption of the DWTP.

Based on the results of the quantitative analysis of energy consumption, the DWTP was sized for solar PV utilizing the available land holdings of the plant. The techno-economic feasibility of solar PV development was evaluated using SAM. It was concluded that:

- For S-1, the development of 11.5 MW PV system with battery storage of 1700 MWh could potentially act as a standalone system to support the plant's total electric load of 56.3 MWh day^{-1}. The PV system was found to be economically feasible, for a net present value of \$5.4 million, and utilizing a land area of 0.25 km^2. If battery storage was not provided, the 11.5 MW PV system could potentially support 47% of the electric load.
- For S-2, the development of a 500 kW PV system with battery storage of 75 MWh, was found to be economically feasible, for a net present value of \$0.24 million, utilizing a land area of 0.01 km^2. The system was able to offset 100% of the load it was designed for, representing about 5% of the total energy consumption; however in the absence of battery storage only 2.2% of the total energy consumption could be offset using the 500 kW PV system.
- The real estate acreage of the DWTP was found to be sufficient for the development of solar PV.
- Development of solar PV only became economically feasible after the federal and state incentives were incorporated in the analysis.
- LCOE for the PV system in standalone mode was found as 2.12 cents kWh^{-1}. However, grid price parity was not achieved for the PV system.

- Economic feasibility of the solar PV was found to be sensitive to changes in debt%, inflation rate, loan term, loan interest rates, and discount rates. Changes in these parameters can render the solar system as financially unfeasible.
- Reduction in battery prices can tremendously help solar PV to become a viable source of electricity generation for the entire 24-hour duration of the day.
- Net reduction in carbon emissions because of solar development was estimated. It was found that for scenario S-1, S-2, in standalone mode, the reduction in carbon emissions was found to be 9500 and 450 metric tons CO_2eq year^{-1}, respectively.
- It was also determined that changing the plant's location from southwestern US (higher solar insolation levels) to US east coast (lower solar insolation level) would require larger PV system size and battery storage capacity and thus increased costs. The results were found to be most sensitive to property tax rate, among the parameters changed between the two locations (sales tax, state income tax, property tax, electric rates). Property tax exemption or partial property tax rate incentives have promising implications for solar development in the area.

This methodology can be applied to other DWTPs for attainment of sustainability goals by using solar PV for electricity generation. The deployment of solar PV will help achieve the effects of increased public and environmental health and climate benefits.

CHAPTER 5: INCORPORATING SOLAR TO OFFSET THE ENERGY CONSUMPTION OF A 300 MGD DRINKING WATER TREATMENT PLANT

This chapter deals with meeting objective two of this research. A large-scale water treatment plant of 300 MGD capacity was analyzed, by first understanding the water-energy nexus of the plant, finding the unit-process based energy consumption and then offsetting the energy consumption of the plant by using solar PV.

5.1 Introduction

Sustainability of energy, water and land are inextricably linked with each other as discussed in Section 1.2 Several current issues warrant the need to understand the nexus between water, land and energy in an integrated manner. Increase in population naturally places increased demands on the energy, land and water sector. U.S. Census Bureau projects global population of 8.9 billion by 2040 compared to the 7.0 billion population in 2012, which is a 21% increase (U.S. Census Bureau, 2017). Water, land and energy demands are also influenced by urbanization, industrialization, food and energy security policies and higher living standards.

According to a study by United Nations Organization (UNO), globally, by the year 2050, water demands are expected to increase by 55% (UNO, 2014). USEIA projected the world energy consumption to increase by 48% between the yeas 2012- 2040 (USEIA, 2017b). Brown et al. (2013) projected an increase of 3% without considering climate change and up to 34% under the changing climate in U.S. freshwater withdrawals between the years 2005-2060. Between the years 2010-2050, primary energy consumption in the U.S. is expected to increase from 97.4 quad Btu to 106.9 quad Btu (USEIA, 2017c).

One of the environmental impacts of the water-energy nexus is greenhouse emission. Currently, energy is generated primarily using fossil fuels. Greenhouse gas emissions associated with energy generation, anthropogenically induced land conversion and water life cycle processes contribute to environmental pollution and degradation of community health (Al-Ansari et al. 2017, Shahzad et al. 2017, Burnham et al. 2016, Denholm & Kulcinski, 2004; Marchal et al. 2011). Greenhouse gas emissions are projected to increase globally by 50% by the year 2050, mainly due to increase in energy demands. Due to conversions of forested land areas into croplands, net carbon dioxide emissions are estimated in the range of 4-8x10^{12} kg (Marchal et al. 2011).

Given that nearly all types of energy generation require water, the nexus between energy and water has been the focus of much research (Berardy & Chester, 2017; Bukhary et al. 2017a; Huang et al. 2017; Bukhary et al. 2016; Nanduri & Saavedra-Antolínez, 2013; Scanlon et al. 2013). Climate change may affect weather patterns related to temperature and precipitation causing extreme conditions of droughts and floods. This may affect the availability and quality of water for energy generation. Limited water availability and pollution under climate change may contribute to the use of less quality water for freshwater production, requiring the use of new technologies for treatment of water such as nano-filtration, ultra-filtration, reverse osmosis, UV disinfection and ozonation. These technologies are energy-intensive, and may shift the energy trends of water sector.

Warmer and dryer climate as well as longer and more intense droughts is predicted for southwestern United States (Cayan et al. 2016; MacDonald, 2010; Jardine et al. 2013). For the southwest, policies regarding water rights add an important dimension to water energy nexus, especially in the context of limited water availability. Changing climate may also lead to land degradation.

Different approaches can be applied to achieve sustainable utilization of energy, land and water resources including water management strategies and using energy efficient equipment. Friction losses and water leaks in water delivery systems can increase energy expenditure. Various water conservation measures can be adopted, including reduction in per capita water demand by conserving residential outdoor water use (using sprinklers, through turning green landscape and lawns to xeriscape, reducing architectural fountains, covering swimming pools), conserving residential indoor water use (improved appliances, reduce-flow showerheads, low-flow toilets, or cost-based incentive) and increased use of reclaimed water (golf courses) (Stave, 2003). Use of energy efficient equipment such as pump systems as well as system automation can lead to energy savings.

Using renewables is another approach to decrease the environmental impacts of nexus and achieve sustainability. For example, solar photovoltaics (PV) and wind have the potential to generate electricity by utilizing less quantities of water. Carbon emissions are also decreased substantially because of reduced dependence on fossil fuel based energy generation (Garfin et al. 2014; Meldrum et al. 2013; Tan & Zhi, 2016). Solar PV has the additional advantage of development as utility-scale generation and distributed generation technology. Other benefits include energy assurance, creation of green jobs, reduced emissions of greenhouse gases and healthier quality of life. Bhandar et al. (2017) found that rural electrification composed of 5 kW solar PV, 3 kW wind power, and a 20 kW hydroelectric plant led to improved quality of life for 250 households located in the mountains of Makawanpur, Nepal.

Solar energy application has certain physical and economic constraints. Large land area is required for development of solar PV, and successful development depends on ample land availability. If sufficient land resources are not available then rooftop solar is also an option. To avoid significant costs related to land preparation, and to minimize land-use impacts of solar development, the site should be flat, or gently sloping with sparse vegetation. Moreover, permits for solar installation are issued for land areas which are not protected habitat and which do not fall under the category of culturally, historically, or archeologically significant areas (Solar PEIS, 2012).

Initial investments are typically high for solar projects, which can be offset by low operation and maintenance costs during operational life of the solar facility (Hernández-Moro & Martínez-Duart, 2013). In recent years, the efficiency of the PV panels has increased significantly with a marked decrease in price, a trend projected to continue over coming years. As for now, governmental support and subsidizes are still required for solar PV projects to be economically feasible (Hagerman et al. 2016; Rodrigues et al. 2016). Reduction in current battery storage prices can significantly alter the way energy is generated today as PV coupled with battery storage can lead to reliable supply of electricity throughout the 24 hours of the day. PV systems coupled with battery can be analyzed for grid parity for viability.

Solar energy can potentially be used to meet the rising energy requirements of the water sector and consequently decrease carbon emissions (Rothausen & Conway, 2011). PV systems can be utilized to meet the energy demands of energy-intensive water operations such as irrigation and pumping (Benghanem & Arab, 2007; Ali & Behera, 2016, Li et al. 2017; Maammeur et al. 2017; Mahmoud & El Nather, 2003), treatment of wastewater (Cho et al. 2014; García-García et al. 2015; Han et al. 2013; Valero et al 2010; Zakkour et al. 2002; Zhang et al. 2013), treatment of brackish water (Byrne et al. 2015; Darwish et al. 2016; Forstmeier et al. 2008; Gude 2015; Khanzada et al.

2017; Richards et al 2017; Shalaby 2017) and drinking water treatment (Bukhary et al. 2017a; Bukhary et al 2017b; Pichel et al. 2016; Soshinskaya et al. 2014).

Solar water-energy nexus approach was utilized by Bukhary et al. (2017a) for a small DWTP located in U.S., whereas Bukhary et al. (2017b) utilized similar approach for treatment of drinking water in Pakistan. Based on literature review, it can be seen that few studies have employed the solar water-energy nexus approach for DWTPs. The objective of this study was to analyze quantitatively the water-energy nexus of large-scale water treatment by:

a) Determining energy consumption of the processes utilized for water treatment including ozonation, coagulation, flocculation, filtration, chlorination and residual management.
b) Determining environmental impacts of the nexus in terms of carbon emissions
c) Analyzing solar PV as an energy source for water treatment
d) Comparing existing available acreage of the treatment plant against computed acreage for installation of distributed solar.
e) Performing cost analysis for solar PV and if it achieves grid parity.

5.2 Study Area

The selected DWTP was located in one of the fastest growing urban landscapes of the United States. The city with a population of 2.08 million in 2015, more than doubled in the last 2 decades. It is an arid region, with a mean yearly precipitation of 105.7 mm. The city is located in a valley with the valley floor situated 487.7 m above sea level. It covers an area of 1554 km^2.

The primary source of water supply was a lake reservoir, which accounted for about 90% of water needs of the valley. Remaining water needs were met by groundwater wells, which accounted for 10 % of water supply, and mainly used during summer season to fulfill peak demand.

Tremendous energy for pumping is required to move water from the lake to the valley, for a lift of about 365.8m. The water is lifted through two of its intake stations to the two drinking water treatment plants, of which one is selected for this study. Then the water is distributed to the valley, for indoor and outdoor usage. The wastewater generated through the indoor usage is conveyed to the one of the three wastewater treatment plants. After treatment, the water has an outfall in the lake, which leads to the provision of "return flow credits" to the valley.

5.3 Data Sources

The data used in the current study was obtained from the selected DWTP managers. It consisted of a raw water quality report (Table 5.1), process flow diagram (Figure 5.1) and operational details of various treatment processes involved. The existing landholdings of the DWTP were accessed using ArcGIS. For estimation of net reduction in carbon emissions, data sources and parameters for carbon emissions in units of $gCO_2eq\ kWh^{-1}$ (Moomaw et al. 2011) and southwestern state's energy-source mix for electricity generation (USEIA, 2016d) are shown in Table 5.2. The parameters for various components of the selected PV system consisting of modules, inverters, and battery storage were chosen from the database provided by SAM, whereas the parameters for cost analysis were obtained from recent published literature (Table 5.3).

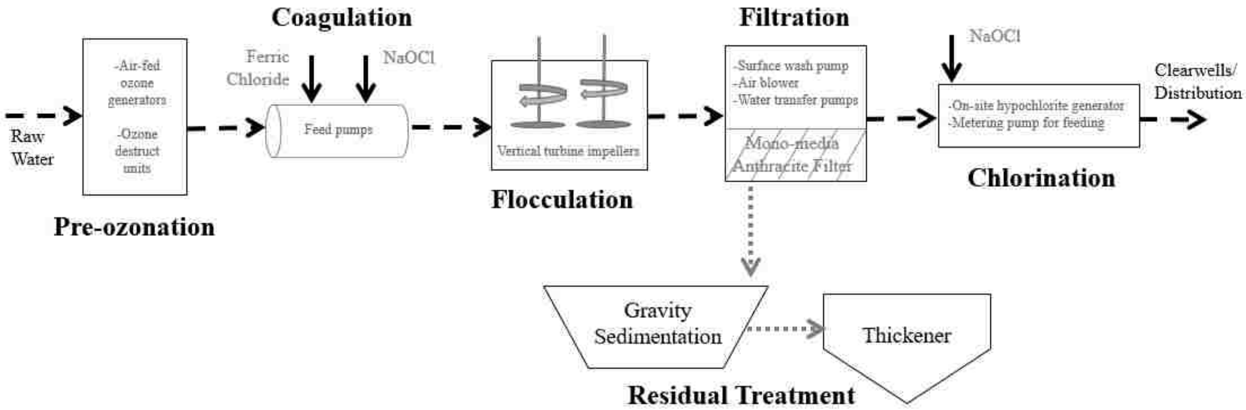


Figure 5.1: Process flow diagram for the drinking water treatment plant.

Table 5.1**:** Water quality report obtained from the drinking water treatment facility managers.

Parameter	Units	Average value	USEPA *MCL/ **SMCL/ guidelines
Conductivity	µS cm^{-1}	975	Not regulated
pH	N/A	8.1	6.5-8.5
Water temperature (winter)	°C	13	Not regulated
Water temperature (summer)	°C	15	Not regulated
Turbidity	NTU	0.51	0.3
Alkalinity	mg L^{-1} as HCO_3	134	Not regulated
Total hardness	mg L^{-1} as HCO_3	294	Not regulated
Noncarbonated hardness	mg L^{-1} as HCO_3	161	Not regulated
Calcium	mg L^{-1}	73	Not regulated
Magnesium	mg L^{-1}	27	150
Potassium	mg L^{-1}	4.5	Not regulated
Sodium	mg L^{-1}	84.5	Not regulated
Bromide	mg L^{-1}	0.09	Not regulated
Chloride	mg L^{-1}	80	250
Nitrate	mg L^{-1}	0.45	10
Sulfate	mg L^{-1}	237	500
Arsenic	µg L^{-1}	0.003	10

*MCL: Maximum contaminant level
**SMCL: Secondary maximum contaminant level

Table 5.2: Carbon emissions (obtained from Moomaw et al. 2011) and State's electricity source mix (obtained from USEIA, 2016d) for various energy sources.

Energy Sources for Electricity Generation	Carbon Emissions (gCO_{2eq} kWh^{-1})	State Electricity Source Mix
Coal	1001	23.51
Natural Gas	469	56.41
Petroleum	840	0.07
Nuclear	16	0
Hydropower	4	7.42
Bio-power	18	0.1
Geothermal	45	8.5
Wind	12	0.95
Solar	46	3.04

Table 5.3: Financial Parameters used for economical assessment using SAM.

	Parameter	Unit	Values for PV System 1MW or greater
Direct Cost	Module	\$ $Watt^{-1}$	0.87
	Inverter	\$ $Watt^{-1}$	0.29
	Battery Bank	\$ $Watt^{-1}$	160
	Balance of equipment cost	\$ $Watt^{-1}$	0.29
	Installation labor	\$ $Watt^{-1}$	0.13
	Contingency	%	4
Indirect capital Cost	Permitting, environmental studies, grid interconnection	\$ $Watt^{-1}$	0.1
	Engineering and developer overhead	\$ $Watt^{-1}$	0.57
O&M Cost	Fixed annual cost	$ /kW/year	15
Project Term Debt	Debt Fraction	%	100
	Loan Term	Year	25
	Loan rate	% $year^{-1}$	3
Analysis Parameters	Analysis period	Year	25
	Inflation Rate	%	2.5
	Real Discount Rate	%	8
Tax and Insurance Rates	Federal income tax rate	% $year^{-1}$	28
	State income tax rate	% $year^{-1}$	0.0
	Sales tax	%	8.1
	Insurance rate	% of installed	0.25
	Salvage value	costs	20
Property Tax	Property tax rate	% $year^{-1}$	0.0 (state incentive)

5.4 Methodology

In this study, energy consumption for energy driving units of the DWTP was determined first. Next, the determined energy consumption was used as load input for System Advisor Model (SAM). The model was used for the design, land requirements and cost analysis of the PV system to offset the energy requirements of the DWTP. Finally, corresponding net reduction in carbon emissions was identified due to PV development. Detailed description of the methodology utilized is as follows:

5.4.1 Process Energy Driving Units

The selected DWTP employed a direct filtration treatment train to treat 300 MGD of water. The screens were not required since the lake water intake was about 30.5 m deep. The process flow diagram of the DWTP utilized is shown in Figure 5.1. Raw water entered the DWTP and was preozonated. Next, the water was flash mixed with the ferric chloride coagulant by employing jet pumps and a deflector plate while passing through two 213.4 cm diameter conduits. Then the water was filtered through 20 mono-media filters, chlorinated by utilizing sodium hypochlorite generated on-site. Finally, the finished water was stored for distribution. Energy driving units for the various unit processes involved are explained as follows:

5.4.1.1 Pre-ozonators

Ozonation is utilized for disinfection, typically as a pre-treatment or a post-treatment process. Ozone (O_3) gas, an unstable and reactive gas is used for destroying algae, viruses and other microorganisms, thus making ozone a powerful disinfectant. Ozone is also effectively employed for color and odor removal as well as some heavy metals.

For ozonation, feed gas can be either air or oxygen; oxygen-enriched air can also be used. Air produces 1.5-2.5% by weight ozone, whereas oxygen produces 3-5% by weight ozone. Ozonation design encompasses various units namely: (1) Feed gas preparation unit (2) Ozone generator (3) Contact basin (4) Ozone mixing system (5) Off-gas destruct unit.

Feed gas needs to be prepared before it is used for ozone generation. That includes the removal of dust, moisture or oil from the feed-gas whether it is oxygen or air. This reduces maintenance activities and is necessary to prevent the reduction in efficiency or the life span of the ozone generator. Moisture removal is most important which is accomplished by using a refrigerant dryer, compressor and desiccant dryer. Air feed system maybe low, medium or high-pressure systems. For oxygen fed systems, oxygen maybe generated on-site for large systems by using vacuum pressure swing adsorption of oxygen from air or cryogenic production. For smaller systems, oxygen can be acquired in form of a liquid or gas.

For ozone generation, the methods used are either using UV radiation or corona discharge. For UV radiation method, light is passed through feed gas generating a photochemical reaction producing ozone. This method typically used for small systems has low efficiency. For large systems, corona discharge cell is used. Ozone is generated by application of a high-voltage current across two electrodes, separated by 0.3-3.0 mm discharge gap through which feed gas flows. Ozone generator may be either low frequency-high voltage or high-frequency-low voltage systems.

Ozone is dispersed into the water under pressure in contact basins. Ozone feed rate varies between 1-5 mg l^{-1}. Contact time depends on CT values, where residual concentration varies between 0.3-0.9 mg l^{-1}. Ozone is mixed in the water using static mixer, porous plate diffusers or venture-type nozzles. The exhaust gas from contact basin is destroyed in off-gas destruct unit. Design and energy consumption of the unit was determined using the guidelines provided by Rakness, (2005) and Stover et al. 1986.

5.4.1.2 Feed System for Coagulation

Application of coagulant destabilizes collides in water and assists in floc formation. Coagulant aid application accelerates the floc formation process. The effectiveness of the operation depends on thoroughly mixing the chemicals with raw water, which is achieved through static mixers, mechanicals mixers or jet diffuser pumps. For the selected DWTP, flash mix system provided means of mixing the coagulant and coagulant aid with disinfected raw water prior to flocculation process.

Jet pumps were used to mix coagulant in two 213.4 cm conduits midway between ozone contacts and flocculation basins to provide necessary reaction time for the chemicals at one location for formation of flocs downstream. The coagulant utilized was ferric chloride. Sodium hypochlorite was also applied. Equation used for determining the energy consumption for the jet pump is shown in Table 5.4. Ferric chloride and sodium hypochlorite were applied via a pipe routed through the center of nozzle, which discharged just in front of the deflector plate.

Table 5.4: Equations utilized to determine the energy consumption of energy driving units of the drinking water treatment plant.

s.no.	Energy Driving Unit/References	Equation
1.	Pump/ (Mays, 2005; WEF, 2009)	$\boldsymbol{E_p} = \frac{(\gamma)(Q)(H)(t_r)}{e}$ Where, Ep = Energy consumption of the pump (kWh day^{-1}), γ = specific weight (kN m^{-3}), Q = flow (m^3 sec^{-1}), H = total dynamic head (m), and t_r= motor run time (hours day^{-1}) e = wire-to-water efficiency
2.	Flocculator / Crittenden et al. (2005)	$\boldsymbol{E_f} = \frac{(G^2)(\mu)(Q_f)(t_s)(t_r)(n_f)}{f}$ Where, E_f = Energy Consumption of the flocculator (kWh day^{-1}), f= motor efficiency, G= root-mean-square velocity gradient (sec^{-1}), μ=dynamic viscosity (N-s m^{-2}) n_f = number of flocculation basins, Q_f =flow rate in each flocculation basin (m3 $minute^{-1}$), ts =detention time per stage (minute) tr= motor run time (hr day^{-1})
3.	Jet Pump/ Hendricks, (2006)	$\boldsymbol{E_j} = \frac{(Q)(\gamma)(t_r)(v_{jet})}{2e}$ Where, Ej = Energy consumption of the jet pump (kWh day^{-1}), v_{jet} is the jet velocity emerging from the orifice (m s^{-1}),
4.	Air blower / Qasim (1998)	$\boldsymbol{E_b} = \frac{(w)(R)(T)(t_r)}{8.41q}\left[\left(\frac{P_2}{P_1}\right)^{0.283} - 1\right]$ Where, E_b= Energy Consumption of the mixer (kWh day^{-1}), w=air mass flow (kg s^{-1}), R=Universal gas constant (kJ k^{-1} mole°K), T=air temperature at inlet (°K), P_1= absolute pressure at entrance (Pascal), P_2 =absolute pressure at exit (Pascal), q= efficiency, 8.41 is constant for air (kg k^{-1} mole), n=(k-1) k^{-1}=0.283 for air

5.4.1.3 Vertical Turbine Flocculators

Coagulation process is followed by the flocculation process, which involves slow mixing achieved through vertical turbine flooculators or paddle wheels. Slow mixing assists in floc formation. These flocs are later separated through the processes of filtration. The coagulation process involves flash mixing to disperse the coagulant within the feed water, whereas flocculation process involves slow mixing to enhance the contact between the coagulant and the feed water and for the subsequent formation of flocs. Slow mixing is required for flocculation, for providing sufficient contact between the coagulant and the particulates suspended within the water.

Vertical turbine flocculators design criteria provided by Crittenden et al., (2005) was used. Velocity gradient between 10-80 s^{-1} was used; maximum tip speed was between 2-3 m sec^{-1}, while rotational speed between 10-30 rev min^{-1} was used.

5.4.1.4 Filtration Backwash System

Next, the flocculated water was filtered using dual-media filters. The filtration process removed suspended solids from the flocculated water. Dual-media filtration design provided by Reynold and Richards, (1996) was used. Dual-media consisted of anthracite and sand to provide a finished water quality of $\leq$ 0.3 NTU. Filtration rate of 13.5 m hr^{-1} was used. Clean bed head loss was determined utilizing the Ergun equation (Crittenden et al. 2005).

The energy consumer for the filtration process was the filtration backwash system. The system consisted of three surface wash pumps, three centrifugal air blowers and three backwash pumps. The equations used for determination of energy consumption are shown in Table 5.4. Surface wash pumps were designed as jet pumps, which were suspended above the filter media surface. The purpose was to break the crust formed on the surface of the filter media due to heavy clogging. Air blowers are used for air-scour cleaning of the filter media. Then the filter-media is backwashed using backwash pumps.

5.4.1.5 On-site Sodium Hypochlorite Generator

For the DWTP, Sodium Hypochlorite was used to incorporate residual effect in the distribution system. This was because during primary disinfection, ozone is destroyed without leaving residual in the system. Sodium hypochlorite was then used as a secondary disinfectant to maintain residual in the system under U.S. Environmental Protection Agency (USEPA) regulations.

Sodium hypochlorite was generated on-site due to safety concerns related to the use of chlorine gas. Sodium hypochlorite was generated on-site using electrolysis process, which involved using electricity in electrolytic units containing sodium chloride brine solution. Electricity consumption was determined using the guidelines provided by White, (2010). Liquid sodium hypochlorite was applied to the treated water using feed pumps. Two feed pumps were provided, where one was used as a backup. The mixing was achieved in the clearwell by utilizing baffles, designed using the criteria provided by USEPA and Lee & Lin (2007).

First, the process involves storing sodium chloride in a saturator tank. Next, brine solution is prepared by passing softened water through saturator ring where water absorbs sodium chloride. The brine solution is then pumped to electrolytic cells, and sodium hypochlorite solution is generated which finally flows into storage tanks. Hydrogen gas is produced as a by-product, which is released into the atmosphere after being diluted.

5.4.1.6 Additional Pump Operations

Other than the pump operations already discussed, zinc orthophosphate (ZO) was added to prevent corrosion of pipes as well as fluorosilicic acid (FA), a source of fluoride, which is important for teeth protection. Finished water was stored in clearwells on site. Finally, the pumping operation was required to distribute the finished water to the city.

Wastewater generated due to backwash operation was treated using clarifiers and then thickeners where suspended solids settled under gravity. Both processes were designed using the criteria provided by Crittenden et al. (2012). The water recovered from the application of the clarifier and thickener was recycled through the DWTP. The energy driving units for the operation were the pumping operation used for the transfer of water and generated sludge.

5.4.2 PV System

PV system can potentially be used to meet the energy demands of the DWTP. Design and cost analysis of a potential PV system was achieved using System Advisor Model, a modeling platform utilized to make performance and cost predictions for renewables including PV (Freeman et al. 2013; Gilman & Dobos, 2012). Various studies have used SAM for analyzing solar technologies (Kalogirou, 2013b; Thevenard and Pelland, 2013; Said et al. 2015, Malagueta et al. 2014; Malvoni et al. 2017, Song & Choi, 2016, Cassard et al. 2011). System advisor model (SAM) is used to analyze performance and economics of renewables over its design life.

PV design warrants several inputs. This includes electric load and weather information. Computation of energy consumption as discussed in Section 5.4.1 was used as an input for electric load. For weather data, SAM contains a library of Typical Meteorological Year data, which is site-specific weather information. TMY2 and TMY3 weather information can be selected. For the site TMY3 dataset was chosen, an updated version of weather dataset spanning between the years 1976-2005, compared to TMY2 dataset, which spans 1961-1990.

The PV design also requires the input of characteristics of the PV system related to modules, inverters and battery storage. Selections for PV modules, inverters and battery storage, and their related characteristics were made from the database provided by SAM. Additional inputs required for the design of the PV system were either using the inputs of the desirable size of array and DC-to-AC ratio, or the desirable number of modules and inverters. Battery storage was used to meet the energy requirements of the DWTP during the absence of daylight since the plant is operational for the 24-hour duration of the day. Battery bank storage can be designed by either utilizing the inputs of the number of battery cells in series and the number of battery strings in parallel, or by utilizing the desirable bank capacity and voltage.

To conduct cost analysis, additional inputs include rate of the electric utility, initial investment costs related to PV system and other cost factors over the lifetime of the system. Financial inputs for SAM are shown in Table 5.3. These parameters were determined by reviewing the publications of Fu et al 2016; Kang & Rohatgi, 2016; Krupa & Harvey 2017; Lai & McCulloch 2017; Mundada et al 2016; Musi et al 2017; Reiter et al 2016.

The feasibility of using solar PV was determined using the financial metrics of net present value (NPV) and levelized cost of electricity (LCOE). NPV is the present value of the difference between cash inflows and outflows, and is estimated in amount of dollars. LCOE is representative of the life cycle costs of the solar system, based on its present value, utilizing the units of cents kWh^{-1}. NPV and LCOE can be estimated using the following equations.

$$NPV = \sum_{t=1}^{T} \frac{I_t}{(1+d)^t} - I_O$$

$$LCOE = \frac{\sum_{t=0}^{T} \frac{C_t}{(1+d)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+d)^t}}$$

Where t= time period, T= analysis period, d=discount rate, Io=capital costs, I_t= net inflow of cash during time t, C_t= costs incurred during time t, and E_t is the energy generated in kWh during time t. LCOE value may or may not be adjusted for inflation. Inflation-adjusted value is called real LCOE, whereas nominal LOE is not adjusted for inflation.

NPV incorporates the time value of money, based on the concept that the present value of money earned today is greater than the same amount of money earned in the future. A project is deemed profitable if the NPV is positive and unprofitable if the NPV is negative. NPV was the principal financial parameter used for this study. This is because other popular metrics such as payback period are undesirable because of complexity in calculations when incorporating various federal and state taxes and incentives. Even though NPV is not scaled, it gives value to the scale of investment, unlike LCOE and payback period.

5.4.3 Carbon Emissions

Operation of the DWTP utilizing PV as an energy source would result in decreased carbon emissions. PV system does not generate emissions during its operational life, but during manufacturing, transportation, and dismantling of a PV system some emissions are generated.

Estimation of carbon emissions were made by taking the product of electricity source mix data of the state and the related carbon emission data for the sources of petroleum, coal, natural gas, solar PV, wind energy, hydroelectricity, geothermal energy, nuclear energy and bio-power (Table 5.2). Data for electricity source mix helps in estimation of emissions related to the traditional grid-electricity generation. Carbon emissions were reduced when PV design was incorporated to decrease the dependence of the DWTP on the traditional electricity grid. The corresponding reduction was estimated by subtracting the emissions generated by the plant when using PV system from the emissions generated by the DWTP using the traditional electricity grid.

5.4.4 Land Area Requirements

In order to estimate the existing empty land acreage of the DWTP, the software ArcGIS was used. SAM estimated the land demands of a PV system by using the following equation.

$$Land\ Requirements = \frac{A_m N_m}{GCR}$$

Where, Am= area of a PV module and Nm= total number of modules being used by the PV system, GCR= ground coverage ratio. GCR determines the east-west distance between the PV arrays. GCR value incorporates the additional area requirements for performance of maintenance activities and avoidance of self-shading.

For calculation purposes in SAM, GCR value varies between 0.01-0.99, implying large east-west distance between the arrays to negligible east-west distance. For the current analysis, a GCR value of 0.3 was utilized.

5.4.4 Scenarios analyzed

For the development of PV system, techno-economic analysis was conducted for drinking water treatment only, excluding distribution pumps. Four scenarios were analyzed. For scenario 1(SC-1), development of PV was considered to meet the energy demands of the drinking water treatment. Further scenarios were analyzed to meet the energy demands of DWTP by excluding the process of ozonation [Scenario 2 (SC-2)], sodium hypochlorite system [Scenario 3 (SC-3)], and ozonation and sodium hypochlorite system [Scenario 4 (SC-4)]. Analysis was conducted for the scenarios, in standalone mode (with storage) and grid-connected mode (without storage). Further, the analysis was conducted for two geographical locations, southwest US where the plant is located, and US east coast.

5.5 Result and Discussion

This section describes the results for analyzing the energy consumption of various unit processes of the DWTP, and then the performance and cost analysis of the PV system.

For the selected DWTP, raw water entered the plant and was ozonated. Ozonation was used as a primary disinfectant and applied as a pre-treatment process. High- purity oxygen was used as feed gas generated using vacuum pressure swing adsorption system. Ozone was generated at 3.6% concentration by weight, whereas the ozone dose used was 1.55 mg l^{-1}. Ozone production was about

1,800 kg day^{-1}. 1.4-log inactivation of cryptosporidium, 9-log inactivation of giardia, and 18.8-log inactivation of virus was achieved utilizing pre-ozonation. Energy consumption for the system is shown in Table 5.5.

Next, the water was coagulated using ferric chloride and flash mixed using jet pumps. Flash mix system consisted of two stages installed in series within each of the two 84 inch conduits. In the first stage, coagulant chemical was applied whereas in the second stage sodium hypochlorite was applied via jet pumps. Mixing was achieved because of high hydraulic shearing action created by interaction between the water jet from the nozzle impacting the deflector plate and the main water flow in the conduit.

Eight flow trains were provided to flocculate 300 MGD of flow using vertical turbine flocculators. Flocculation was achieved in 3 stages for decreasing velocity gradients of 70, 40 and 25 sec^{-1} and for Reynolds number greater than 10,000.

After the process water was ozonated, coagulated and flash-mixed, it was filtered using 20 dual-media filters, having an area of 184.5 m^2. The filter media comprised of 1.83 m of anthracite, followed by 0.2 m of sand placed above the underdrains. Each filter consisted of two cells, each having an area of 92.2 m^2. Filtration rate used was 13.5 m hr^{-1}. Media size for anthracite was 1.2 mm, whereas for sand was 0.61 mm. Clean bed head loss was found to be 0.57 m. Two out of twenty filters were provided for redundancy purposes. The operational duration for the surface wash pumps were 3 minutes, followed by air scour for 8 minutes. Duration for backwashing was 15 minutes. Frequency of backwash was daily hence a value of 24 hours was used. The energy consumption determined for the backwash filtration system is shown in Table 5. Filtration recovery was found to be 97%.

Since ozone has no residual, chlorination is still required to protect the finished water against the microbial contamination in the distribution system. Nine on-site sodium hypochlorite generators were used for out of which two were provided as a backup. The generators has an installed capacity was about 8,165 kg day^{-1} equivalent chlorine. Liquid sodium hypochloride was added to the finished water using five10 hp and three 20 hp feed pumps, out of which two were used as a back-up (Table 5.5). Finished water was distributed using eight 40 MGD water distribution pumps, each with a motor size of 3500 hp. Two additional pumps were provided as a backup.

Backwash filtration system generates wastewater, which is treated using clarifiers and thickeners. At first, the wastewater was conveyed to two equalization basins, an additional basin was provided as a backup. Next, the water was pumped to two clarifiers for solid settling under the effect of gravity. The generated effluent is recycled through the DWTP, whereas the generated sludge pumped to two thickeners. The energy consumers of the thickener were the water transfer pumps and the sludge transfer pumps.

Total energy consumption for the DWTP was about 577 MWh day^{-1} (508 Wh m^{-3}) while energy consumption required for water treatment excluding water distribution pumps was about 65.5 MWh day^{-1} (57.7 Wh m^{-3}). Results showed that the largest consumer of energy for the plant was the pumping operation. Energy consumption for the water distribution pumps was about 512 MWh day^{-1} (450.4 Wh m^{-3}), while the pumping operations for the treatment of drinking water amounted to 5.71 MWh day^{-1} (5.1 Wh m^{-3}), thus utilizing about 89.6% of the total energy consumption. Among processes utilized for treatment of water, on-site sodium hypochlorite generator was the largest consumer of energy, consuming about 57% of the overall energy consumption (32.9 Wh m^{-3}) (Table 5.5, Figure 5.2). Second largest consumer was the ozonation process (19.5 Wh m^{-3}). Third largest consumer of electricity was the coagulation process that employed jet pumps for flash mixing, with an energy intensity of about 2.6 Wh m^{-3}. Processes of flocculation (1.2 Wh m^{-3}) and filtration (1.32 Wh m^{-3}) each consumed about 2% of the overall energy consumption. Smallest consumers of energy were the processes involved in residual management as well as the addition of ZO and FA, each consuming about 0.1% of the overall energy consumption. For SC-1, SC-2, SC-3 and SC-4, energy consumption was determined as 65.5, 43.3, 28, and 5.8 MWh day^{-1}, respectively.

Sensitivity analysis was performed for the energy consumption estimates related to pumping operation for the treatment plant. Wire-to-electric efficiencies of the pumps were increased by 5% and 10%, which resulted in 0.42% (65.2 MWh day^{-1}) and 0.8% (65 MWh day^{-1}) decrease in the total energy consumption (65.5 MWh day^{-1}) of the water treatment units respectively. Whereas decreasing wire-to water efficiencies by 5% (65.8 MWh day^{-1}) and 10% (66.1 MWh day^{-1}) resulted in increased total energy consumption by 0.46% and 0.97%. This increase and decrease is small because the major energy driving units for the water treatment units were the processes of ozonation and sodium hypochlorite generation system unaffected by the changes in wire-to-water efficiency.

Plappally and Lienhard, (2012) reported energy consumption of various unit processes of water treatment based on literature review, including 8–22 Wh m^{-3} for rapid mixers for coagulation, 5-14 Wh m^{-3} for gravity filtration, and 30-200 Wh m^{-3} for ozone generators. Lee et al. (2017) reported energy intensity values for desalination, water and wastewater treatment and transport for urban areas as 0-3700 Wh m^{-3} for source water extraction and transport, 30-4230 Wh m^{-3} for treatment, and 30-580 Wh m^{-3} for distribution, 160 Wh m^{-3} for wastewater collection, and 180-10,000 Wh m^{-3} for wastewater treatment. In California, about 3% of the total electricity consumption is utilized for drinking water supply and treatment, while 1 % is used for wastewater treatment, according to a study by California Energy Commission (CEC) (CEC, 2006). The report estimated energy intensity for raw water conveyance, drinking water treatment, water distribution, and wastewater treatment as 0-3650 Wh m^{-3}, 26 Wh m^{-3}, 320 Wh m^{-3}, and 290-650 Wh m^{-3}, respectively.

Table 5.5: Energy consumption estimates of various unit processes of drinking water treatment plant.

s. no.	Unit Process	Energy Driving Units	Energy Consumption (kWh day^{-1})	Energy Intensity (Wh m^{-3})	Estimated Motor Size (hp)	Plant Motor Size (hp)
1.	Pre-ozonation		22200	19.5	1240.4	1200
2.	Coagulation	Jet Diffuser Pump (Coagulant addition)	1467.7	1.3	62.7	61
		Jet Diffuser Pump (Sodium Hypochlorite addition)	1467.7	1.3	62.7	61
3.	Flocculation	Vertical Turbine Flocculators (Stage 1)	955.3	0.8	5.4	5.4
		(Stage 2)	311.9	0.3	1.7	1.5
		(Stage 3)	121.8	0.1	0.7	0.74
4.	Filtration	Surface Wash Pump	19.4	0.02	76.4	75
		Backwash Water Pump	93.8	0.1	251.6	250
		Air Scour Blower	176.8	0.2	598	600
		Filter-to-waste Pump	1120.1	1.0	3004.3	3000
5.	Chlorination Disinfection	Sodium Hypochlorite Generator	36000	31.7	214.3	217
		Feed Pump	722.5	0.6	20.2	20
		Feed Pump	723.2	0.6	10.1	10
6.	Zinc Orthophosphate	Metering Pump	26.6	0.02	0.74	0.75
7.	Fluorosilicic Acid addition	Metering Pump	18.7	0.02	1	1
8.	Equalization Basin	Water Transfer pump	29.1	0.03	19.5	n/a
9.	Clarifier	Sludge Transfer Pump	17.6	0.02	19.6	n/a
		Water Transfer Pump	17.6	0.02	19.6	n/a
10.	Thickener	Sludge Transfer Pump	17.6	0.02	19.6	20
		Water Transfer Pump	1.1	0.001	14.6	15
11.	Finished-Water Distribution	Distribution Pumps	511.5×10^3	450.4	3572	3500

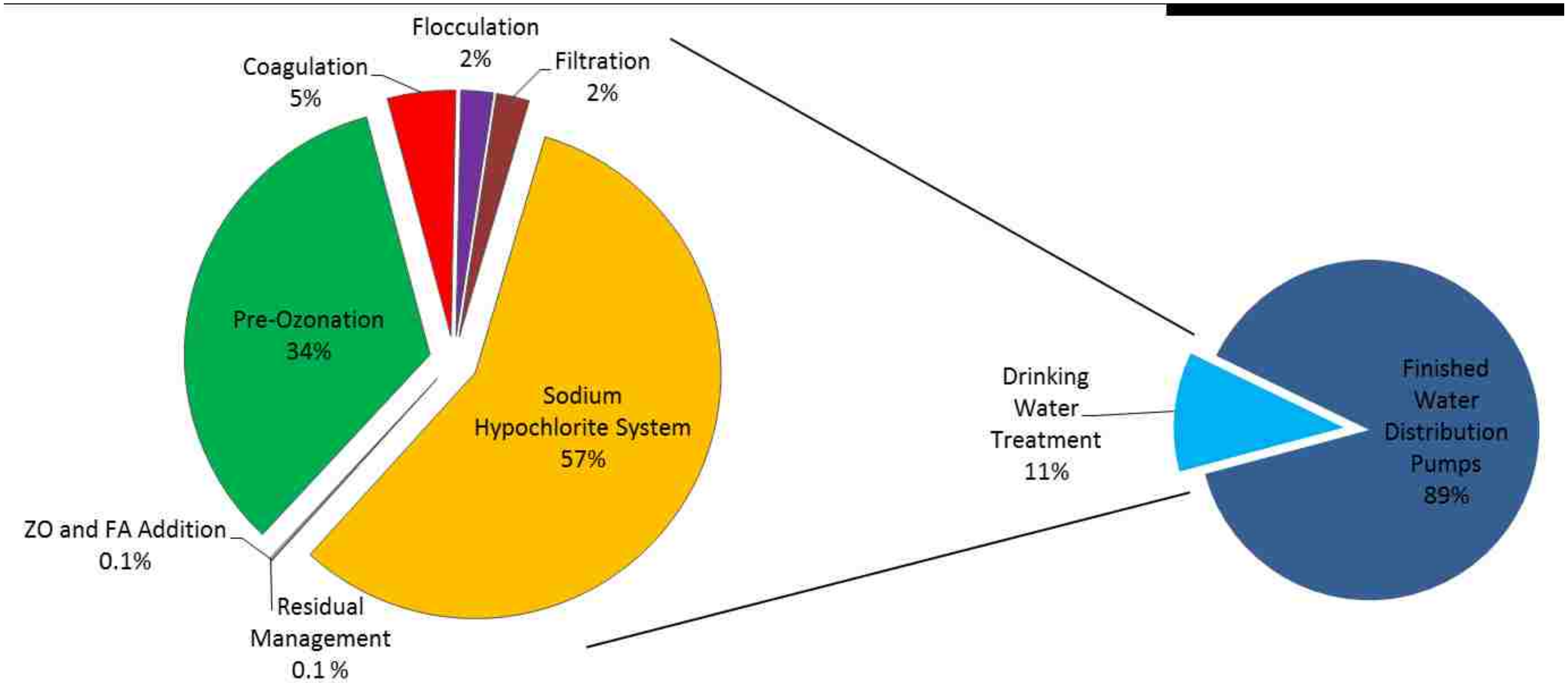


Figure 5.2: Energy consumption by percentage for the drinking water treatment plant.

To incorporate sustainability into the design and operation of the DWTP, PV was utilized. Design and economic analysis of the PV system was achieved using SAM. Energy consumption determined for unit processes was utilized as the electric load for sizing solar PV. Rate charges applied were for large-scale service for high voltage transmission (> 25000 V). The DWTP did not qualify for net metering since the electric utility allowed net metering rates to be applied to only residential and small commercial facilities for solar system with capacities of 1 MW or less, energy consumption of < 10 MWh $month^{-1}$, and demand of < 50 kW.

For the PV system, tracking type selected was 2-axis, and ground-mounted. Parameters for the selected solar module, inverter and battery type are shown in Table 5.6 (Freecleansolar, 2017; Invertersupply, 2017; Wholesalesolar, 2017d). Battery storage was provided to meet energy demands for 24-hour operation of the plant.

For SC-1, SC-2, SC-3 and SC-4, energy consumption was determined as 65.5, 43.3, 28, and 5.8 MWh day^{-1}, representing 11%, 7.5%, 5%, and 1% of the total energy consumption, respectively. These estimates were the electric load input for SAM. Analysis utilizing SAM resulted in 12 MW, 8 MW, 5 MW and 1.1 MW solar systems, with battery storage capacities of 1.06 $x10^3$ MWh, 800 MWh, 460 MWh, and 120 MWh for scenarios SC-1, SC-2, SC-3 and SC-4, respectively (Table 5.7, Figure 5.3). About 47% of the energy requirement was fulfilled using PV system while the remaining 53% of the load was supported using battery storage. If battery storage was not provided for these scenarios, then the same PV systems could offset about 5.3% (12 MW system, NPV $6.7M, net capital cost $37M), 3.5% (8 MW system, NPV $4.4M, net capital cost $24.7M), 2.3% (5 MW system, NPV $2.8M, net capital cost $15.4M), and 0.5% (1.1 MW system, NPV $0.36, net capital cost $3.1M) of the total energy consumption for SC-1, SC-2, SC-3 and SC-4, respectively.

The real and nominal LCOE values for systems without battery storage were 0.57 and 0.7 cents kWh^{-1}, respectively. The aforementioned estimations for scenarios without incorporating battery storage represent the effect of the battery storage on the overall cost and performance of the PV system. The PV systems were grid-connected. NPV was positive for all the analysed scenarios; hence, the development of solar PV was economically feasible. Results generated in this study may serve as a gauge for design and analysis of treatment plants using similar processes. Some plants might not be using ozonation process or they might not have an on-site sodium hypochlorite generation system represented by SC-2, SC-3, and SC-4.

The development of solar PV is dependent upon governmental support. Removing the 30% ITC resulted in negative NPV for both S-1 and S-2 scenarios. Further, this resulted in LCOE values higher than the average price of electricity for commercial consumer in the state which was 7.98 and 8.08 cents kWh^{-1} for the years 2016 and 2017, respectively (USEIA, 2017a). Hence, for the selected DWTP, grid price parity was not achieved.

Sensitivity analysis was conducted by quantifying the influence of interest rate (0-5%), ITC (0-50%), and electricity rates ($\pm$25-50%). As shown by Figure 5.4, changing interest rate between 0-5%, resulted in the NPV varying between positive \$38.7 million to negative \$12.4 million for SC-1, while varying between positive \$4.1 million to negative \$15.5 million for SC-4. For LCOE, decreasing the interest rate resulted in decreased LCOE values and vice versa (Figure 5.5). Changes in investment tax credit in the range of 0-50% greatly affected the economic feasibility of the project. PV system development reduces energy costs incurred due to the use of utility grid. However, if the electric rates are too low, PV system development may no longer be feasible as shown by Figure 5.6.

Figure 5.4-5.6 show that LCOE values for PV system with battery storage more affected by changes in interest rate and ITC, then for those without storage. NPV values for PV system with battery storage supporting large loads are more affected by changes in interest rates and ITC, then PV systems supporting smaller loads with or without storage. LCOE values for PV system with or without battery storage are not affected by changes in electric rates since electric rates are not part of the PV system lifecycle costs. NPV values for PV system with or without battery storage supporting large loads are more affected by changes in electric rates, then PV systems supporting smaller loads with or without storage.

Development of PV with battery storage would lead to reduced carbon emissions. For SC-1, SC-2, SC-3, and SC-4, net reduction in carbon emissions was estimated as 11000, 7300, 4700, and 980 metric ton CO_2eq year^{-1}, respectively; while without battery storage, the reduction in emissions were estimated as 5200, 3400, 2200, 460 metric ton CO_2eq year^{-1}, respectively. For the eight water distribution pumps, carbon emissions were estimated at 86,000 metric ton CO_2eq year^{-1}. As shown by the results, adverse impacts of the water-energy nexus can be reduced by using solar for energy generation. USEPA, (2013) estimated that carbon emissions in the amounts of 40.8 million metric tons are related to water and wastewater treatment operation.

Table 5.6: Photovoltaic system design characteristics used in SAM.

	Parameter	**Unit**	**Value**
Module	Module Name	-	Solarland USA SLP230-60
	Module Area	m^2	1.64
	Module Material	-	Multi C-Si
	Nominal Efficiency	%	14
	Maximum Power Pmp	Watt	230
	Maximum Power Voltage Vmp	Volt	30.2
	Maximum Power Current Imp	Ampere	7.6
	Open Circuit Voltage Voc	Volt	36.9
	Short Circuit Voltage Isc	Ampere	8.3
Inverter	Inverter Name	-	SMA: SB9000TL-US-12
	Weighted Efficiency	%	97.7
	Maximum AC Power	Watt	9000
	Maximum DC Power	Watt	9303
	Nominal AC Voltage	Volt	208
	Maximum DC Voltage	Volt	600
	Maximum DC Current	Ampere	31.4
	Minimum MPPT DC voltage	Volt	300
	Nominal DC Voltage	Volt	345.6
	Maximum MPPT DC Voltage	Volt	480
Losses	Average Annual Soiling Loss	%	3
	Connection Losses	%	0.5
	DC wiring Losses	%	2
	AC Wiring Losses	%	1
	System Performance Degradation Rate	%	0.5
Battery Storage	Battery Name	-	Deep Cycle AGM
	Cell nominal voltage	Volt	2
	Internal Resistance	m Ohm	1.6
	Cell Capacity	Ah	1150
	Max C-rate of Charge	$hour^{-1}$	0.12
	Max C-rate of Discharge	$hour^{-1}$	0.12
	Minimum State of Charge	%	10
	Maximum State of Charge	%	95
	Minimum Time at Charge State	min	10

Table 5.7: Results for the techno-economic analysis of the PV system using System Advisor Model for scenario SC-1 (load input of water treatment units only i.e. excluding water distribution pumps), SC-2 (SC-1 excluding ozonation process), SC-3 (SC-1 excluding sodium hypochlorite generation), and SC-4 (SC-1 excluding sodium hypochlorite generation and ozonation process).

	Parameter	Unit	SC-1 (11% of load)	SC-2 (7.5% of load)	SC-3 (4.9% of load)	SC-4 (1% of load)
Module	Nameplate Capacity	kW	12,000	8,000	5,000	1,100
	Number of Modules	-	52,140	34,752	21,270	4,776
	Modules per String	-	12	12	12	12
	Strings in parallel	-	4,345	2,896	1,810	398
	String Voc	Volt	442.8	442.8	442.8	442.8
	String Vmp	Volt	362.4	362.4	362.4	362.4
	Total Module Area	$x10^3$ m²	85.6	57.1	35.7	7.8
	Total Land Area	$x10^3$ m²	285.3	190.2	119	26.3
Inverter	Total Capacity	kWac	9,999	6,660	4,167	918
	Number of inverters	-	1,111	740	463	102
	DC to AC Ratio	-	1.2	1.2	1.2	1.2
Battery	Nominal Bank Capacity	MWh	1,060	800	460	120
	Nominal Bank Voltage	Volt	350	350	350	350
	Cell in Series	-	175	175	175	175
	Strings in Parallel	-	2,634	1,988	1,143	299
	Battery efficiency	%	91.8	92	91.9	92
Financial	Net Present Value	$ million	4.93	2.98	2.1	0.36
Metrics	Levelized cost of electricity (nominal)	Cents kWh^{-1}	2.07	2.25	2.13	2.39
	Levelized cost of electricity (real)	Cents kWh^{-1}	1.68	1.82	1.73	1.94
	Net Capital Cost	$ million	298.6	222.1	128.9	33.1
	Electricity bill without system (year 1)	$ million	1.37	0.91	0.59	0.13
	Electricity bill with system (year 1)	$	4,340	4,340	4,340	4,340

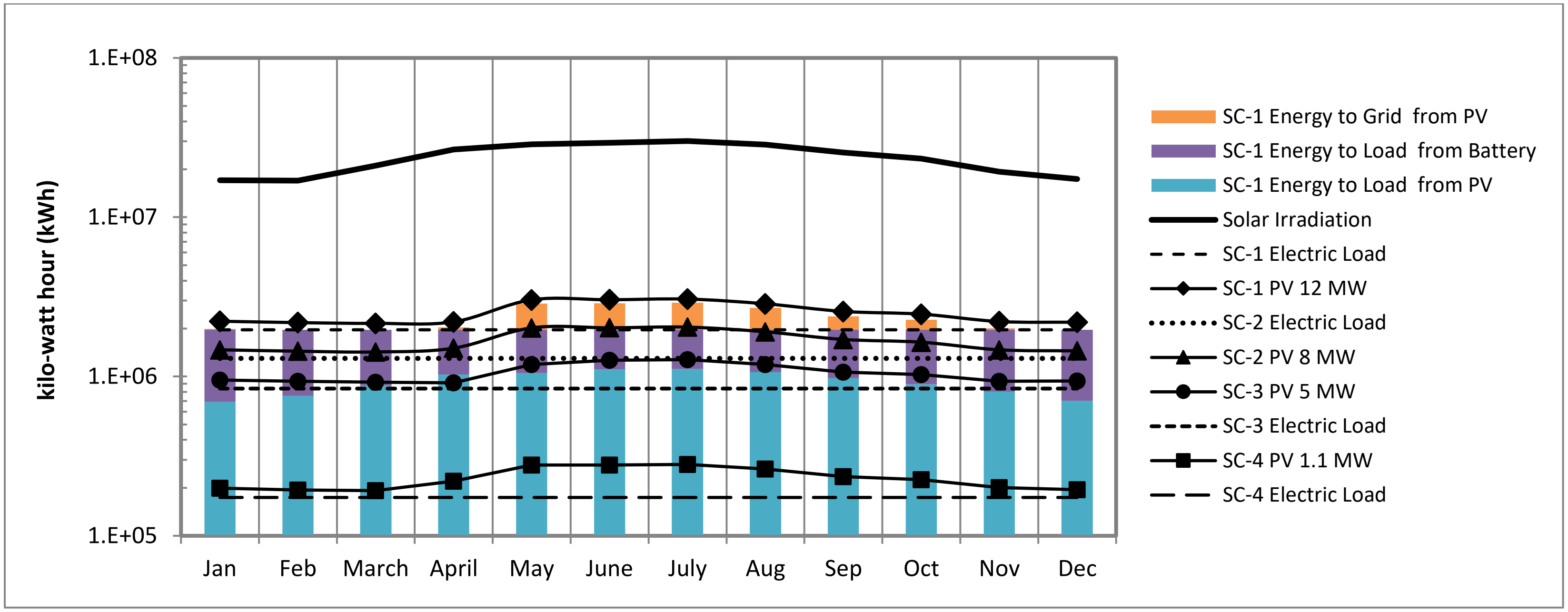


Figure 5.3: Inputs of electric load and solar irradiation, and outputs for photovoltaic (PV) energy generation with battery storage for the drinking water treatment facility for scenario SC-1 (load input of water treatment units only i.e. excluding water distribution pumps for PV system design), SC-2 (SC-1 excluding ozonation process), SC-3 (SC-1 excluding sodium hypochlorite generation), and SC-4 (SC-1 excluding sodium hypochlorite generation and ozonation process).

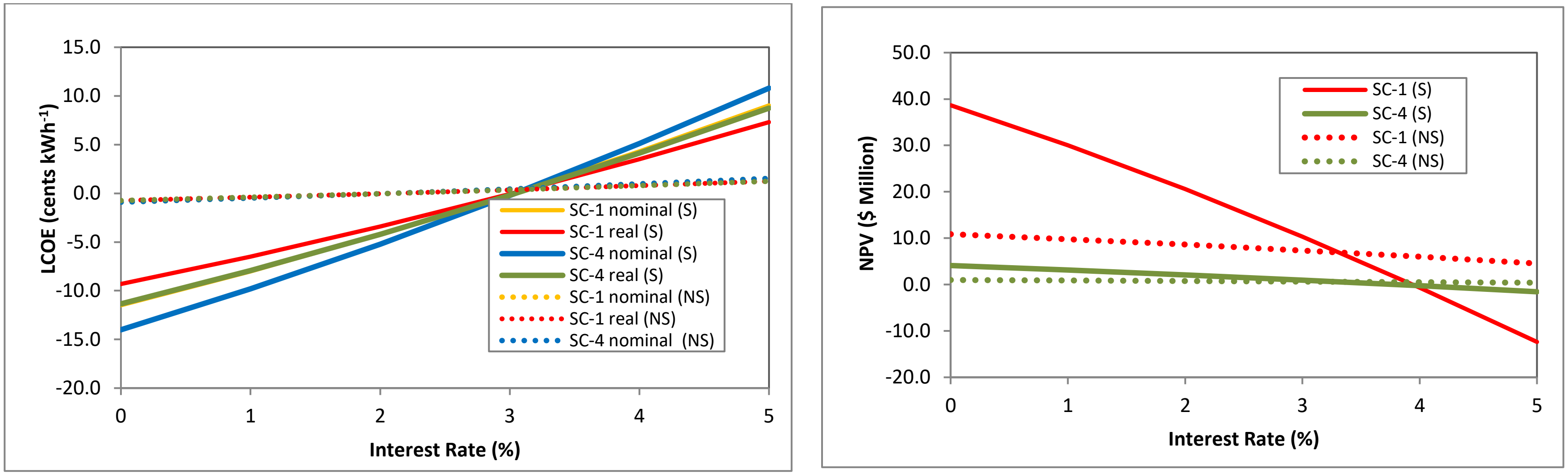


Figure 5.4: Sensitivity analysis showing the quantified influence of interest rate on NPV and LCOE (nominal and real) for scenario SC-1 (load input of water treatment units only i.e. excluding water distribution pumps for PV system design), and SC-4 (SC-1 excluding sodium hypochlorite generation and ozonation process) with storage (S) and with no storage (NS).

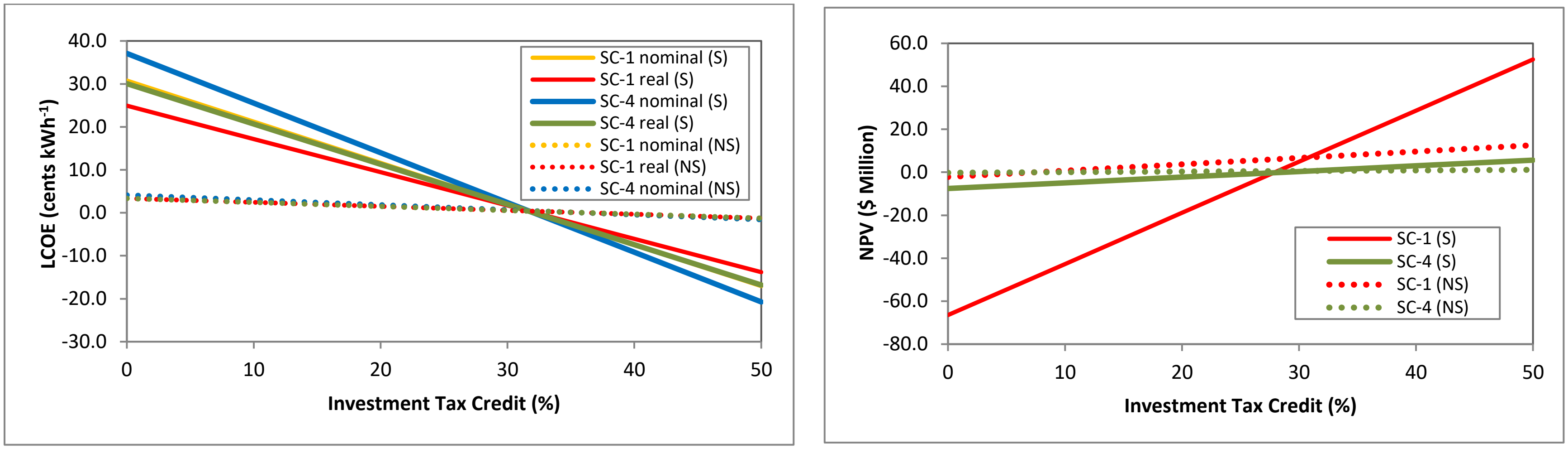
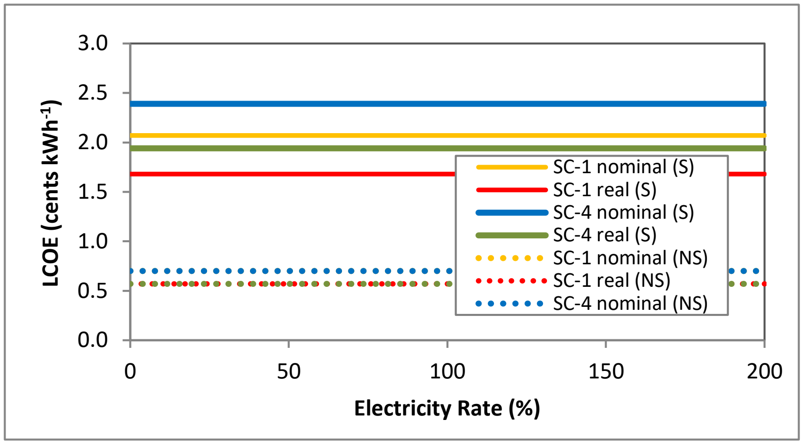


Figure 5.5: Sensitivity analysis showing the quantified influence of investment tax credit on NPV and LCOE (nominal and real) for scenario SC-1 (load input of water treatment units only i.e. excluding water distribution pumps for PV system design), and SC-4 (SC-1 excluding sodium hypochlorite generation and ozonation process) with storage (S) and with no storage (NS).



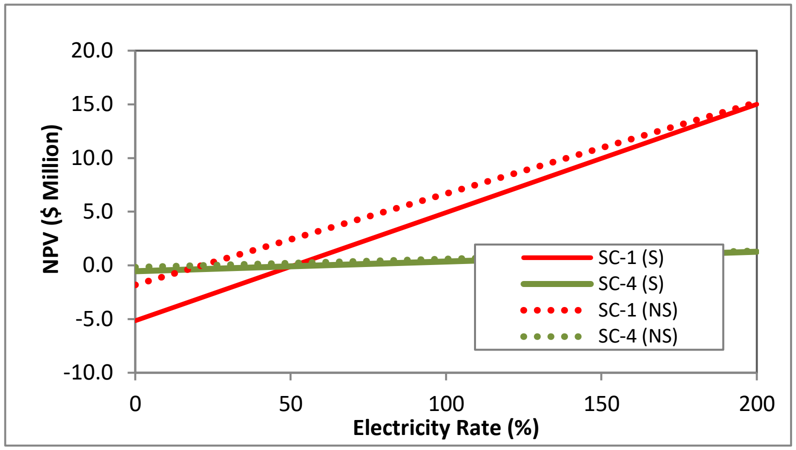


Figure 5.6: Sensitivity analysis showing the quantified influence of electricity rate (±50-100%) on NPV and LCOE (nominal and real) for scenario SC-1 (load input of water treatment units only i.e. excluding water distribution pumps for PV system design), and SC-4 (SC-1 excluding sodium hypochlorite generation and ozonation process) with storage (S) and with no storage (NS).

Within the fenced area of the DWTP, about 1.6 km^2 of land area may be utilized for the development of solar PV. The value was determined using ArcGIS. As shown by Table 5.7, land requirements for installation of PV system for all the four scenarios analysed, were determined to be much less than 1.6 km^2. The land area is primarily flat with low shrubs; thus, PV system can be deployed with minimum land preparation and disturbance.

A hypothetical scenario was examined by changing the location of the treatment plant to the US east coast. The location selected was White Plains, New York having direct insolation levels of 3.5 kWh m^{-2} day^{-1} compared to 6.3 kWh m^{-2} day^{-1} for the site selected in southwest. Financial parameters were not changed except sales tax rate for Westchester County where White Plains city is situated, which was taken as 4.375% and state income tax rate, which was taken as 8.82% for New York. The incentives incorporated were 30% ITC and 100% state sales tax exemption (DSIRE, 2017). The system did not qualify for other incentives. Property tax rate of 2% was used. The electric rate input utilized, downloaded from SAM database for electric rates, was based upon the rates of New York Power Authority for large general service.

The analysis showed that for SC-1, the 12 MW PV system with 1060 MWh battery capacity was able to offset 100% of the 65.5 MWh day^{-1}electric load when sited in the southwestern location (scenario SC-1, Table 5.7). However, the same system when located in White Plains, New York was able to offset 81% of the total electric load, while without battery storage was able to offset 38% of the total load analyzed. Hence, when battery storage was provided, it offset another 43% of the load. The system size was changed to evaluate if it was possible to offset 100% of the load. It was determined that a 16.5 MW PV system using battery storage capacity of 1500 MWh was able to offset 100% of the 65.5 MWh day^{-1}electric load, for White Plains, New York location, where battery storage was able to offset about 60% of the load. However, the system was not economically feasible. The NPV was negative \$16 million, with LCOE value of 12 cents kWh^{-1}, while the net capital costs increased by \$108.3 million.

Sensitivity analysis for the financial parameters that were changed when analyzing for the southwestern US and New York location, property tax rates were shown to have the largest effect. For New York location, property tax rate when changed from 2% to 1.2% would render the PV system financially feasible for SC-1 NPV of \$2.4 million and LCOE value of 3.8 cents kWh^{-1}. Property tax rate may vary depending upon location of the property. A property tax exemption or partial property rate incentives have the potential of greatly promoting the development of solar facilities in the state.

Another hypothetical scenario was examined to evaluate the effect of property tax exemption in US east coast by changing the location of the treatment plant to Massachusetts State, which provides a financial incentive of 100% property tax exemption for 20-year period among other incentives for solar facilities (DSIRE, 2017). The selected location was Boston, Massachusetts having solar insolation levels of 3.7 kWh m^{-2} day^{-1} compared to 7.1 kWh m^{-2} day^{-1} for the southwestern site. Financial parameters were not changed except sales tax rate, which was taken as 6.25% and state income tax rate, which was taken as 5.1% for Massachusetts. The incentives incorporated were 30% ITC and 100% property tax exemption for 20-year period (DSIRE, 2017). Property tax rate of 2% was used. The electric rate input utilized was based upon the rates of National Grid of Massachusetts for large general service for commercial or industrial facilities with demands > 2000 kW (National Grid, 2018). The results of the analysis showed that the 12 MW PV system using battery storage capacity of 1060 MWh was able to offset 100% of the 65.5 MWh day^{-1}

electric load when sited in the southwestern location (scenario SC-1, Table 5.7); however the same system when located in Boston, Massachusetts was able to offset 84% of the total load analyzed. The system size was changed to evaluate if it was possible to offset 100% of the load. It was determined that a 17 MW PV system using battery storage capacity of 1400 MWh was able to offset 100% of the 65.5 MWh day^{-1}electric load, if the plant was located in in Boston, Massachusetts. The NPV was \$3.1 million, with LCOE value of 2.11 cents kWh^{-1}. However the net capital costs increased by \$93 million.

Comparing the results between New York and Massachusetts location, the effect of the incentive of partial property tax exemption can be seen. Changes in geographical location of the plant from southwest (higher solar insolation levels) to east coast US (lower solar insolation levels) would require larger PV system size and battery storage capacity to offset the same electric loads, however the system was able to offset about 81-84% of the total load analyzed without changing the size of the system. This system was able to offset large portion of load because it was designed for worst-case scenario of the winter months for the southwest location.

In today's scenario of urbanization, climate change effects on land systems, over-exploitation of land for agricultural purposes and land degradation due to pollution, among many multi-faceted factors, sustainable use of land area becomes vital. This encompasses ensuring minimal environmental impacts while also maintaining the multi-functionality of land area and solar PV maybe one of the approaches to ensure sustainable use of land. Fthenakis & Kim, (2009) estimated life-cycle land transformation for various sources of electricity generation including coal, coal, natural gas, nuclear, PV, wind, biomass and hydroelectric and determined PV installations to cause the least land transformation among them. Bukhary et al. (2018) determined PV systems to be favorable for land-limited and water-limited areas.

This study has successfully applied the water-energy nexus approach for drinking water treatment. One aspect that highlights the significance of the energy-water nexus for drinking water treatment is the increased emphasis in recent years, on the placement of stricter water quality standards and the use of improved technologies for drinking water treatment for the removal of pharmaceuticals, disinfection byproducts, endocrine disrupters and other trace organic chemicals (Petrovic´ et al. 2003; USEPA, 2016b). Advanced treatment technologies including ozonation, ultrafiltration, reverse osmosis, and UV disinfection can be used to meet such standards, but these technologies are energy-intensive (Shannon et al. 2008). Such issues warrant exploring renewables for achieving sustainability goals of water treatment systems.

Another aspect, that brings forth the importance of the energy-water nexus for drinking water treatment are rising energy costs, which can be a motivating factor for DWTPs to explore and implement different methods to reduce their overall energy consumption. In the U.S., for a drinking water treatment plant, 40 % of operational and maintenance costs are associated with energy usage and is projected to rise by 20% in the next 15 years due to increasing population and stringent water quality standards (Spellman, 2013). About 80% of the cost associated with water treatment and distribution are electricity related (Goldstein and Smith, 2002). Value of energy is not constant and is much more valuable over peak time; solar PV deployment has the potential to serve as a balanced source of electricity during peak time hours.

Bryan et al. (2016) analyzed the water-energy-land nexus for Australia and evaluated policy implications for the year 2050. Bukhary et al. (2018) analyzed the solar water-energy nexus for utility-scale solar installations in the southwestern U.S. based on the renewable portfolio standards. Chen et al. (2018) made quantitative assessments of land area utilized for cultivation (39%) and associated water withdrawal (29%) within the context of global supply chain. Howells et al. (2013) evaluated the effects of climate change on water-energy-land nexus by developing a model for integrated resource management and policy analysis.

5.6 Conclusion

The aim of this study was the application of water-energy nexus approach for the DWTP by (a) determining energy consumption of the processes utilized for water treatment (b) using PV as an energy source for treatment facility (c) Performing cost analysis for PV system (d) Quantifying the net reduction of carbon emissions due to PV development. Following conclusions were made:

- Total energy consumption for the DWTP was about 577 MWh day^{-1} (508 Wh m^{-3}) while energy consumption required for water treatment excluding water distribution pumps was about 65.5 MWh day^{-1} (57.7 Wh m^{-3}). Pumping operation was the largest consumer of energy. Energy consumption for the water distribution pumps was about 512 MWh day^{-1} (450.4 Wh m^{-3}), while the pumping operations for the treatment of drinking water amounted to 5.71 MWh day^{-1} (5.1 Wh m^{-3}), thus utilizing about 89.6% of the total energy consumption.
- For SC-1, SC-2, SC-3 and SC-4, energy consumption was determined as 65.5, 43.3, 28, and 5.8 MWh day^{-1}, respectively. On-site sodium hypochlorite generation system was the largest consumer of energy, consuming about 57% of the overall energy consumption (32.9 Wh m^{-3})

whereas pre-ozonation was the second largest consumer of energy (19.5 Wh m^{-3}), among the processes utilized for treatment of water.

- For SC-1, SC-2, SC-3 and SC-4, the capacity of the PV system was determined as12, 8, 5, and 1.1 MW, with battery storage capacities of 1.06 $x10^3$, 800, 460, and 120 MWh, respectively, offsetting about 11%, 7.5%, 5%, and 1% of the total energy consumption of the plant (577 MWh day^{-1}), respectively. Without battery storage, grid-connected PV system could offset about 5.3%, 3.5%, 2.3%, and 0.5% of the total energy consumption (577 MWh day^{-1}) for SC-1, SC-2, SC-3 and SC-4, respectively. For SC-1, SC-2, SC-3 and SC-4, NPV was found to be positive; hence, solar PV was economically feasible for all four scenarios analyzed.
- LCOE for the PV system in standalone mode was found as 1.7 cents kWh^{-1}. However, grid price parity was not achieved for the PV system.
- For SC-1, SC-2, SC-3, and SC-4, net reduction in carbon emissions was estimated as 11000, 7300, 4700, and 980 metric ton CO_2eq $year^{-1}$, respectively; while without battery storage, net reduction in carbon emissions was estimated 5200, 3400, 2200, 460 metric ton CO_2eq $year^{-1}$, respectively.
- It was also determined that changing the plant's location from southwestern US (higher solar insolation levels) to US east coast (lower solar insolation level) would require larger PV system size and battery storage capacity. The results were found to be most sensitive to property tax rate, among the parameters changed between the two locations (sales tax, state income tax, property tax, electric rates). A property tax exemption or partial property tax rate incentives have promising implications for solar development in the area.

CHAPTER 6: CONTRIBUTIONS AND RECOMMENDATIONS

6.1 Introduction

The overall objective of the study was the application of water-energy nexus approach for solar development in the southwestern United States. To meet the overall objective, the work was divided into two main research tasks.

The first research task was related to utility-scale solar development in the SEZs of six southwestern states by quantitatively analyzing water availability and usage, land availability and usage, and associated reductions in carbon emissions based upon the renewable portfolio standards and goals of the six states. Key findings determined PV to be most favorable for land-limited or water-limited areas in the southwest. In contrast, trough wet-cooling technology and power tower were found to be least favorable for water-limited regions and land-limited regions, respectively. Total water resources and land area within the SEZs of Nevada and New Mexico were determined to be sufficient to meet the solar carve-outs. Findings also determined non-availability of unappropriated water resources within most SEZs, suggesting a lack of co-ordination between the regional energy policy-makers and water sector.

The second research task was related to distributed solar development to meet the energy requirements of three DWTPs, located in the southwest. The three relatively small (10 MGD), medium (90 MGD) and large plants (300 MGD), treated groundwater, river water, lake water, respectively by utilizing in-line filtration, conventional filtration, direct filtration processes, respectively. The three treatment plants were designed and energy consumption was determined for the energy driving units. Quantitative assessment for the energy consumption for the various unit processes determined pumping operation to be the largest consumer of energy for all three plants. System Advisor Model was used for techno-economic assessment of the PV system. The development of solar PV successfully resulted in offsetting the energy consumption of the three plants, in stand-alone and grid-connected modes. NPVs were found to be positive rendering the PV systems to be economically feasible; however, the economic analysis was sensitive to the various incentives and financial parameters used as an input. The existing landholdings were found to be sufficient for the development of solar PV for the three plants.

Following is a discussion of the contributions, limitations, and recommendations of the two research tasks:

6.2 Research Objective 1: Water for Solar Development in the Southwest

The objectives of research task 1 were to (a) generate harmonized water consumption and land estimates for utility-scale solar energy installations in the southwestern US; and (b) to make quantitative assessments of water and land usage and their availability for utility-scale solar development, and associated reductions in carbon emissions based on the renewable portfolio standards of six southwestern US states-Arizona, California, Colorado, Nevada, New Mexico, and Utah, by generating a simulation model between the years 2015-2030. Contributions, limitations, and recommendations of this study are as follows:

6.2.1 Contribution

The research made the following contributions:

This was the first study to determine harmonized estimates related to on-site water withdrawal and consumption for solar plant construction, operations, and dismantling, as well as direct and total land requirements for solar plant. Harmonized estimates were generated through review and screening of over 150 publications, by utilizing the parameters related to southwestern United States. Harmonization performance helped remove inconsistencies and data assumptions across various studies. It was determined that:

- Largest demand with respect to water was determined for CSP trough wet-cooling technology (520 gal MWh^{-1}) whereas the least demand was determined for PV technology (8.6 gal MWh^{-1}), among the various configurations of technologies analyzed.
- CSP-tower (10.4 m^2 MWh^{-1} yr) had the largest effect with respect to land requirement, whereas solar PV and CPV had the smallest effect (6.7 m^2 MWh^{-1} yr).
- Solar PV was shown to be favorable for areas with limited water or land resources.

This was the first study to assess quantitatively the level of support the 19 SEZ located in the six southwestern U.S can provide for utility-scale solar development by simultaneously considering water and land resources of the SEZ and comparing them against the solar water and land demands and determining cutoffs. RPS-based potential of SEZs and the associated reduction in carbon emissions was determined using a simulation model between the years 2015-2030. The following was determined:

- UGW resources were available for some of the SEZs within Nevada and Utah, but there was no USW resource available for any of the 19 SEZs. Limited availability of unappropriated water may hinder the development of utility-scale solar power in the SEZs.

- Moreover, solar development 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.
- Total water (including reclaimed and desalinated water) and land resources within the SEZs may be sufficient for utility-scale solar development 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.
- Net reduction in carbon emissions for solar PV in year 2030 for the six states, was equivalent to GHG emissions generated by 0.3-3.1 million passenger vehicles driven for one year. 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.

6.2.2 Assumptions and Limitations

Following assumptions were used for the analysis:

- In the current study, it was assumed that RPS based solar power development was solely utility-scale, and distributed renewable carve-outs were not incorporated within the simulation model.
- 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 would likely be a mix of different configurations of solar technologies. However, 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. Nevertheless, results of this study could help identify the solar technologies whose increased deployment could likely benefit water-limited or land-limited regions.
- Water availability data was obtained from Tidwell et al. (2014) since it provided data for all six southwestern being analyzed in the current study. Further, the study provided water availability projections and covered the analysis period between 2015-2030, for five sources of water, USW, UGW, WW, BGW AW, which was not available through other sources.
- Various configurations of solar PV (Flat-plate/ fixed tilt, 1-axis, and CPV) and CSP technologies (CSP trough and CSP tower) were analyzed based on the data available.

- 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.

6.2.3 Recommendation

Recommendations for future work are discussed below:

- Harmonized estimates for water and land requirements were based off review and screening of published data. A larger pool of publications may help improve the determined estimates.
- For future work, economic feasibility for solar development can be analyzed within the zones.
- The results revealed that greater understanding of solar energy-water nexus, especially on a local scale, is crucial for successful implementation of energy policies. More work in this area may help avoid water-limited zones becoming a hindrance to solar energy development in the region.
- Solar PV technology may be utilized successfully for electricity generation within water-limited or land-limited areas.
- 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.
- The simulation model generated in this study could be utilized to analyze and compare the performances of renewable energy sources in addition to solar energy.

- Moreover, this model could be replicated for other regions, using data applicable to those regions.

6.3 Research Objective 2: Solar Energy for Drinking Water Treatment

This aim of this study was to apply the water-energy nexus approach for drinking water treatment. One of the environmental impacts of the nexus are carbon emissions, which were reduced by utilizing solar energy to offset the energy consumption of three existing drinking water treatment plants in the southwest. Contributions, limitations, and recommendations of this study are as follows:

6.3.1 Contribution

This study was the first of its kind to evaluate the water-energy nexus of three existing DWTP located in southwestern United States. The three plants differed by capacity (10 MGD, 90 MGD, 300 MGD), raw water source (groundwater, river, lake), and unit processes involved for treatment of raw water (In-line filtration, conventional filtration, direct filtration). Environmental impacts of the nexus are carbon emissions, which were reduced by making unit process-based quantitative assessment of the energy consumption of the three plants, and then using photovoltaics to offset this energy consumption based on available land holdings of the plants and economic feasibility. The following was determined:

- Total energy consumption was determined as 5.6 MWh day^{-1}, 56.6 MWh day^{-1}, and, 577 MWh day^{-1} for the 10 MGD, 90 MGD and 300 MGD plant, respectively.
- Energy intensity was determined as 154 Wh m^{-3}, 165 Wh m^{-3}, and 508 Wh m^{-3}, for the 10 MGD, 90 MGD and 300 MGD plant, respectively.

- Quantitative assessment for the energy consumption determined pumping operation to be the largest consumer of energy, utilizing about 98%, 95%, and 90% of the total energy consumption for the 10 MGD, 90 MGD and 300 MGD plant, respectively.
- Excluding the water distribution pumps, the treatment plant units consumed about 0.11 MWh day^{-1}, 2.7 MWh day^{-1}, and 65.5 MWh day^{-1}, whereas their energy intensities were determined as 3.1 Wh m^{-3}, 7.8 Wh m^{-3}, 57.7 Wh m^{-3}, for 10 MGD, 90 MGD and 300 MGD plant, respectively.
- Energy intensity values were determined for the 10 MGD plant for the processes of coagulation (0.15 Wh m^{-3}), filtration (0.72 Wh m^{-3}), chlorination (0.05 Wh m^{-3}), residual management (1.23 Wh m^{-3}), and lime addition (0.93 Wh m^{-3}). Energy intensity values were determined for the 90 MGD plant for the processes of coagulation (1.95 Wh m^{-3}), flocculation (1.93 Wh m^{-3}), sedimentation (1.2 Wh m^{-3}), filtration (1.3 Wh m^{-3}), chlorination (0.15 Wh m^{-3}), residual management (1.1 Wh m^{-3}), and soda ash system (0.17 Wh m^{-3}). Energy intensity values were determined for the 300 MGD plant for the processes of ozonation (19.6 Wh m^{-3}), coagulation (1.3 Wh m^{-3}), flocculation (1.22 Wh m^{-3}), filtration (1.24 Wh m^{-3}), sodium hypochlorite generation system (31.7 Wh m^{-3}), chlorination feed pumps (1.27 Wh m^{-3}), and residual management (0.07 Wh m^{-3}).
- Energy intensity values generated rigorously for various processes for the three plants may allow a more accurate comparison of plants performance against that of other plants.
- The design equations and results for the energy consumption can be applied to other plants utilizing similar processes.

- A rigorous analysis of energy consumption of the various unit processes involved in drinking water treatment helped identify key design parameters that maybe modified to reduce the energy requirements of treatment plants.
- The development of solar PV successfully resulted in offsetting the energy consumption of the three plants, in stand-alone and grid-connected modes.
- PV systems of capacities 1.5 MW (with a battery bank capacity of 30.2 MWh) and 11.5 MW (battery bank capacity of 1700 MWh), for the 10 and 90 MGD plant has the potential to act as a standalone system and offset 100% of the plants energy consumption. For the 300 MGD plant, energy-intensive water distribution units were not profitable for development of PV system; hence, 12 MW PV system (with a battery bank capacity of 1,100 MWh) was used to offset the energy consumption of the water treatment units only.
- About 50-60% of the electric load could be offset without battery storage using the same PV system capacity for the three plants.
- The existing landholdings of 0.2 km^2, 0.4 km^2 and 1.6 km^2 were found to be sufficient for the PV systems land requirements of 0.03 km^2, 0.25 km^2, and 0.28 km^2, for the 10 MGD, 90 MGD and 300 MGD plant, respectively.
- Reduction in carbon emissions due to PV development with battery storage amounted to 950, 9500, 11,000 metric ton CO_2eq $year^{-1}$ for 10, 90, 300 MGD plant respectively.
- The plant sites showed high potential for solar electricity generation.
- Solar PV development at the scale of small, medium, and large treatment plants was economically feasible with positive NPV, with and without battery-storage systems.

However, it was determined that for large plants, it is not profitable to be in a standalone mode for offsetting the total energy consumption.

- Economic analysis sensitive to changes in debt percentage, inflation rate, loan term, loan interest rates, discount rates, electric rates, and incorporated incentives related to investment tax credit and property tax.
- Reduction in battery prices can tremendously help solar PV to become a viable source of electricity generation for the entire 24-hour duration of the day and help achieve grid parity.
- Existing land-holdings of the selected DWTP were sufficient for the development of solar PV.
- Real LCOE for the PV system in standalone mode was found as 2.5, 2.1 and 1.7 cents kWh^{-1} for the 10 MGD, 90 MGD and 300 MGD plant, respectively. However, grid price parity was not achieved for the PV systems.
- Changes in geographical location of the plants from southwest (higher solar insolation levels) to east coast US (lower solar insolation levels) would require larger PV system size and battery storage capacity to offset the same electric loads, however the system was able to offset about 80-90% of the total load analyzed without changing the size of the system. The economic feasibility was found to be most sensitive to property tax rate, among the various financial input parameters (sales tax, state income tax, property tax, electric rates) changed between the two geographical locations. A property tax exemption or partial property tax exemption incentives have promising implications for solar development in the region.

- Drinking water treatment as shown has typically low thermal demand compared to other industries and hence favorable for solar installations.
- Data generated in this study can serve as a gauge when considering solar energy use in water treatment facilities as a means to save energy and increase sustainability.

6.3.2 Assumptions and Limitations

The assumptions and limitations of the study are as follows:

- The design was based on the maximum day demand flow at the end of design period, which was 10 MGD, 90 MGD and 300 MGD for the three relatively small, medium and large DWTPs and was considered as an extreme case. Other parameters chosen were also reflective of the extreme conditions. Hence, the energy consumption estimate determined was representative of the worst-case scenario for the DWTP, and thus was assumed constant throughout the year.
- Raw water quality characteristics were obtained from the plants' managers and any missing information was reproduced from Crittenden et al. (2005).
- Economic feasibility is dependent upon the selection of financial parameters, based on the review of existing literature published between the years 2016-2017. Changes in the values of these parameters can greatly affect the results of cost analysis. Economic feasibility of the solar PV was found to be sensitive to changes in debt percentage, inflation rate, loan term, loan interest rates, and discount rates.

6.3.3 Recommendation

Recommendations for future work are discussed below:

- In this study, determination of energy consumption was limited to drinking water treatment. For future work, energy consumption related to distribution of water within the community could also be analyzed.
- Results revealed the battery storage prices to be a chief component affecting the economic feasibility of solar projects. Hence, to promote the role of solar PV as a viable and competitive source of electricity generation, and for achievement of grid-parity, battery prices need to be reduced. For future work, this would require application of novel approaches in the field of battery production that could lead to low-cost battery storage systems.
- The selected treatment plants could not qualify for net metering; such regulatory restrictions have the potential to deter investments for distributed solar projects. Further work may include extending the scope of work to include much smaller treatment plants that would qualify for net metering. This has the potential to help small treatment plants to not only achieve economic feasibility for solar deployment, but also earn credits to attain net-zero energy consumption for the treatment plants.
- This methodology can be applied to other DWTPs for attainment of sustainability goals by using solar PV for electricity generation. The deployment of solar PV will help achieve the effects of increased public and environmental health and climate benefits.

APPENDIX

Appendix A-1: Table providing detailed description of physical and technical characteristics of the 19 Solar-Energy Zones in AZ, CA, CO, NM, NV, and UT

S. N.	SEZ	State	SEZ Area (km²)	Physical Characteristics	Technical Characteristics		Annual Precip-itation (mm)
				Location	Road Access/ proximity to SEZ border	Road Access/ proximity to SEZ border	
1.	Agua Caliente	AZ	10.32	Lies in the Palomas Plain, surrounded on the west by the Palomas Mountains and on the north by Baragan Mountain. The Gila River runs 8 km to the south. Sparsely populated surrounding area.	I-8, 19.2 km to south.	I-8, 19.2 km to south.	
2.	Brenda		13.5	Lies within the Ranegras Plain, surrounded by the Bouse Hills to the north, Bear Hills and Plomosa Mountains to the southwest & west, and the Granite Wash Mountains and Harquahala Mountains to the east. Flat landscape. Primarily sandy loams and gravelly sandy loams.	U.S. 60 along southeast	U.S. 60 along southeast	102
3.	Gillespie		11	Surrounded on the southwest by the Gila Bend Mountains and on the northeast by Centennial Wash. Flat landscape. As typical of alluvial fan terrace, soil is primarily extremely and very gravelly sandy loams.	Old U.S. 80, 5 km from east.	Old U.S. 80, 5 km from east.	100-200
4.	Imperial East	CA	23.1	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. Primarily fine sands and loamy fine sands.	I-8 along northeast, State Route 98, through south	I-8 along northeast, State Route 98, through south	<200
5.	Riverside East		598.6	Located within the Mojave Desert, in Chuckwalla Valley, the South Palen Valley, and CDCA. Consists of flat barren plains. Alluvial fan terraces. Development in areas surrounding the SEZ. Primarily gravelly loams.	I-10 along south, State Route 177 through west,	I-10 along south, State Route 177 through west,	80-100
6.	West Chocolate Mountains		43.5	Located in Colorado Desert, surrounded on the west by the Salton Sea, and on the east by the Chocolate Mountains Aerial Gunnery Range. Contains desert washes, including Iris Wash. Gently sloping topography towards the Salton Sea. Solar trough and power tower are not allowed in the SEZ because of high water usage, as well as any installation > 61 m in height.	State Route 111 crosses SEZ north and south	State Route 111 crosses SEZ north and south	100-150

7.	Antonito Southeast	CO	39.3	Lies in the San Luis Valley, which is surrounded by the San Juan Mountains to the west and on the east by Sangre de Cristo Range. The terrain is flat to gently rolling. Very stony loams and cobbly loams.	U.S. 285	U.S. 285	51-203
8.	De Tilla Gulch		4.3	Located in the northwest part of San Luis Valley, which lies in the Rocky Mountains in the San Luis Basin. SEZ terrain is gently sloping. Some development exists in surrounding areas. Soils are primarily gravel to gravel sandy loams.	U.S. 285 along northwest	U.S. 285 along northwest	200
9.	Fournile East		11.7	Lies in the eastern San Luis Valley, on a flat alluvial fan in the high-elevation San Luis Basin. Soils are predominantly loamy sands and loamy fine sands.	U.S. 160 along the south	U.S. 160 along the south	200
10.	Los Mogotes East		10.8	Located in the southwestern San Luis Valley, on a flat alluvial fan in San Luis Basin. Soils are primarily cobbly to very stony loams.	U.S. 285 about 5 km to east	U.S. 285 about 5 km to east	200
11.	Afton	NM	121.2	Lies in the West Mesa of Mesilla Basin, bounded by Robledo Mountain and the Rough and Ready Hills to the north; Aden Hills, Sleeping Lady Hills, West Potrillo Mountains to the west; and Mesilla Valley to the east. Primarily a mix of loamy fine sand, fine sandy loam, fine sand, loam and loamy sand.	I-10 about 5 km to the north	I-10 about 5 km to the north	200
12.	Amargosa Valley	NV	34.3	Lies in the Amargosa Desert, which is bounded on the southwest by the Funeral Mountains and on the northeast by Yucca Mountain. Soils are primarily gravelly sandy loams and gravelly loams	U.S. 95	U.S. 95	170-240
13.	Dry Lake		23	Lies in Dry Lake Valley, surrounded by the Arrow Canyon Range to the west and Dry Lake Range to the southeast. Very gravelly and stony loams.	I-15 along southeast and U.S. 93 along southwest	I-15 along southeast and U.S. 93 along southwest	100
14.	Dry Lake Valley North		101.5	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. Soils are primarily sandy loams, silt loams, loamy sands, and loams	State Route 318, 11 km to west, U.S. 93, 13 km to south.	State Route 318, 11 km to west, U.S. 93, 13 km to south.	130
15.	Gold Point		18.6	Lies within Lida Valley, surrounded by Palmetto Mountains to the west and Stonewell Mountains to the east.	State Route 774 along east, U.S. 9, 14 km to east	State Route 774 along east, U.S. 9, 14 km to east	180-410
16.	Millers		66.9	Situated in Big Smoky Valley, surrounded on the south by Lone Mountain, on the west by Monte Cristo Range, and on the east by San Antonio Mountains.	U.S. 95/U.S. 6, which along south	U.S. 95/U.S. 6, which along south	80-150

17.	Escalante Valley	UT	26.4	Situated in the southern part of Escalante Desert, framed on the northeast by Mineral Mountains, on the south and southeast by the Black Mountains and Antelope Range, and on the northwest by Shauntie Hills and the Wah Wah Mountains. Soil is primarily silt loams.	State Route 56, 24 km south, Lund Highway northeast	State Route 56, 24 km south, Lund Highway northeast	130
18.	Milford Flats South		25.3	Situated in the northeastern part of Escalante Desert, framed on the northeast by Mineral Mountains, on the south and southeast by Black Mountains, and on the northwest by Shauntie Hills, and on the west by the Wah Wah Mountains. Soil is primarily silt loams.	State Route 21/130, about 8 km east. State Route 129 is 5 km northwest.	State Route 21/130, about 8 km east. State Route 129 is 5 km northwest.	200
19.	Wah Wah Valley		23.8	Situated in Wah Wah Valley, bounded on the west and southwest by Wah Wah Mountains, on the south and southeast by Shauntie Hills, and on the east by San Francisco Mountains. Predominantly silty clay loams, fine sandy loams, and sandy clay loams.	State Route 21, through the north half	State Route 21, through the north half	200

REFERENCES

Abrar-ul-Haq, M., Jali, M.R.M. and Nawaz, M.A., 2017. Socio-economic and health benefits of renewable energy using improved cooking stoves: A theoretical perspective. *Renewable and Sustainable Energy Reviews*.

Ahmad, S., 2016. Managing Water Demands for a Rapidly Growing City in Semi-Arid Environment: Study of Las Vegas, Nevada. *International Journal of Water Resources and Arid Environments*, *5*(1), pp.35-42.

Ahmad, S. and Prashar, D., 2010. Evaluating municipal water conservation policies using a dynamic simulation model. *Water Resources Management*, *24*(13), pp.3371-3395.

Ahmad, S. and Simonovic, S.P., 2006. An intelligent decision support system for management of floods. Water Resources Management, 20(3), pp. 391-410.

Ahmad, S. and Simonovic, S.P., 2000. System dynamics modeling of reservoir operations for flood management. Journal of Computing in Civil Engineering, 14(3), pp. 190-198.

Al-Ansari, T., Korre, A., Nie, Z. and Shah, N., 2017. Integration of Greenhouse Gas Control technologies within the Energy, Water and Food Nexus to enhance the environmental performance of food production systems. *Journal of Cleaner Production*.

Al-Sharafi, A., Sahin, A.Z., Ayar, T. and Yilbas, B.S., 2017. Techno-economic analysis and optimization of solar and wind energy systems for power generation and hydrogen production in Saudi Arabia. *Renewable and Sustainable Energy Reviews*, *69,* pp.33-49.

Alharbi, F.H. and Kais, S., 2015. Theoretical limits of photovoltaics efficiency and possible improvements by intuitive approaches learned from photosynthesis and quantum coherence. *Renewable and Sustainable Energy Reviews*, *43,* pp.1073-1089.

Alghoul, M.A., Poovanaesvaran, P., Mohammed, M.H., Fadhil, A.M., Muftah, A.F., Alkilani, M.M. and Sopian, K., 2016. Design and experimental performance of brackish water reverse osmosis desalination unit powered by 2 kW photovoltaic system. Renewable Energy, 93, pp.101-114.

Ali, A. and Behera, B., 2016. Factors influencing farmersʹ adoption of energy-based water pumps and impacts on crop productivity and household income in Pakistan. *Renewable and Sustainable Energy Reviews*, *54,* pp.48-57.

Ali, B., 2017. The cost of conserved water for power generation from renewable energy technologies in Alberta, Canada. *Energy Conversion and Management*, *150*, pp.201-213.

Ali, B. and Kumar, A., 2017. Development of water demand coefficients for power generation from renewable energy technologies. *Energy Conversion and Management*, *143*, pp.470-481.

Amoueyan, E., Ahmad, S., Eisenberg, J.N., Pecson, B. and Gerrity, D., 2017. Quantifying pathogen risks associated with potable reuse: A risk assessment case study for Cryptosporidium. *Water Research*, *119*, pp.252-266.

Ansari, N. and Seifi, A., 2012. A system dynamics analysis of energy consumption and corrective policies in Iranian iron and steel industry. Energy, 43(1), pp. 334-343.

Anwarzai, M.A. and Nagasaka, K., 2017. Utility-scale implementable potential of wind and solar energies for Afghanistan using GIS multi-criteria decision analysis. *Renewable and Sustainable Energy Reviews*, *71*, pp.150-160.

Arent, D., Pless, J., Mai, T., Wiser, R., Hand, M., Baldwin, S., Heath, G., Macknick, J., Bazilian, M., Schlosser, A. and Denholm, P., 2014. Implications of high renewable electricity penetration in the US for water use, greenhouse gas emissions, land-use, and materials supply. Applied Energy, 123, pp. 368-377.

Arnell, N.W., 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. Global environmental change,14(1), pp.31-52.

Asdrubali, F., Baldinelli, G., D'Alessandro, F. and Scrucca, F., 2015. Life cycle assessment of electricity production from renewable energies: Review and results harmonization. Renewable and Sustainable Energy Reviews, 42, pp.1113-1122.

Aslani, A., Helo, P. and Naaranoja, M., 2014. Role of renewable energy policies in energy dependency in Finland: System dynamics approach. Applied Energy, 113, pp. 758-765.

Aslani, A. and Wong, K.F.V., 2014. Analysis of renewable energy development to power generation in the United States. Renewable Energy, 63, pp. 153-161.

Astolfi, M., Mazzola, S., Silva, P. and Macchi, E., 2017. A synergic integration of desalination and solar energy systems in stand-alone microgrids. *Desalination*, *419*, pp.169-180.

Atilgan, B. and Azapagic, A., 2015. Life cycle environmental impacts of electricity from fossil fuels in Turkey. Journal of Cleaner Production, 106, pp.555-564

Averyt, K., Macknick, J., Rogers, J., Madden, N., Fisher, J., Meldrum, J. and Newmark, R., 2013. Water use for electricity in the United States: an analysis of reported and calculated water use information for 2008. Environmental Research Letters, 8(1), p. 015001.

Baharoon, D.A., Rahman, H.A., Omar, W.Z.W. and Fadhl, S.O., 2015. Historical development of concentrating solar power technologies to generate clean electricity efficiently–A review. Renewable and Sustainable Energy Reviews, 41, pp.996-1027.

Bailey, J.R., 2012. Investigating the Impacts of Conventional and Advanced Treatment Technologies on Energy Consumption at Satellite Water Reuse Plants. *University of Nevada Las Vegas Thesis*, 1707.

Barlev, D., Vidu, R. and Stroeve, P., 2011. Innovation in concentrated solar power. Solar Energy Materials and Solar Cells, 95(10), pp.2703-2725.

Bazilian, M., Onyeji, I., Liebreich, M., MacGill, I., Chase, J., Shah, J., Gielen, D., Arent, D., Landfear, D. and Zhengrong, S., 2013. Re-considering the economics of photovoltaic power. *Renewable Energy*, *53*, pp.329-338

Beeby, S. and White, N.M., 2010. Energy harvesting for autonomous systems. Artech House.

Berardy, A. and Chester, M.V., 2017. Climate change vulnerability in the food, energy, and water nexus: concerns for agricultural production in Arizona and its urban export supply. *Environmental Research Letters*, *12*(3), p.035004.

Blair, N., Dobos, A., Freeman, J., Neises, T., Wagner, M., Ferguson, T., Gilman, P. and Janzou, S., 2014. System advisor model, SAM 2014.1. 14: General description. Nat. Renew. Energy Lab., Denver, CO, USA, Tech. Rep. NREL/TP-6A20-61019.

Benghanem, M. and Arab, A.H., 2007. Photovoltaic water pumping systems for Algeria. *Desalination*, *209* (1-3), pp.50-57.

Berckmans, G., Messagie, M., Smekens, J., Omar, N., Vanhaverbeke, L. and Van Mierlo, J., 2017. Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030. *Energies*, *10*(9), p.1314.

Bhandari, B., Lee, K.T., Chu, W.S., Lee, C.S., Song, C.K., Bhandari, P. and Ahn, S.H., 2017. Socio-economic impact of renewable energy-based power system in mountainous villages of Nepal. *International Journal of Precision Engineering and Manufacturing-Green Technology*, *4*(1), pp.37-44.

Blair, N., Mehos, M., Christensen, C. and Cameron, C., 2008. Modeling photovoltaic and concentrating solar power trough performance, cost, and financing with the solar advisor model. Solar 2008, American Solar Energy Society.

BLM Solar, 2014. Bureau of Land Management (BLM) Solar Energy Program. http://blmsolar.anl.gov/sez/ (accessed 10 July 2016).

Boden, T.A., R.J. Andres, G. Marland. 2013. http://cdiac.ornl.gov/trends/emis/top2013.tot (accessed 20 September 2016).

Bosetti, V., Catenacci, M., Fiorese, G. and Verdolini, E., 2012. The future prospect of PV and CSP solar technologies: An expert elicitation survey. Energy Policy, 49, pp.308-317.

Bouchekima, B., 2003a. A small solar desalination plant for the production of drinking water in remote arid areas of southern Algeria. Desalination, 159(2), pp.197-204.

Bouchekima, B., 2003b. A solar desalination plant for domestic water needs in arid areas of South Algeria. *Desalination*, *153*(1-3), pp.65-69.

Bracken, N., Macknick, J., Tovar-Hastings, A., Komor, P., Gerritsen, M. and Mehta, S., 2015. Concentrating Solar Power and Water Issues in the US Southwest (No. NREL/TP-6A50-61376). National Renewable Energy Laboratory (NREL), Golden, CO.

Branker, K., Pathak, M.J.M. and Pearce, J.M., 2011. A review of solar photovoltaic levelized cost of electricity. *Renewable and Sustainable Energy Reviews*, *15*(9), pp.4470-4482.

Brown, T.C., Foti, R. and Ramirez, J.A., 2013. Projected freshwater withdrawals in the United States under a changing climate. *Water Resources Research*, *49*(3), pp.1259-1276.

Brown, K.E., Henze, D.K. and Milford, J.B., 2017. How accounting for climate and health impacts of emissions could change the US energy system. *Energy Policy*, *102*, pp.396-405.

Brownson, J.R., 2013. Solar energy conversion systems. Academic Press.

Bryan, B.A., Nolan, M., McKellar, L., Connor, J.D., Newth, D., Harwood, T., King, D., Navarro, J., Cai, Y., Gao, L. and Grundy, M., 2016. Land-use and sustainability under intersecting global change and domestic policy scenarios: trajectories for Australia to 2050. *Global Environmental Change*, *38*, pp.130-152.

Burkhardt, J.J., Heath, G. and Cohen, E., 2012. Life cycle greenhouse gas emissions of trough and tower concentrating solar power electricity generation. Journal of Industrial Ecology, 16(s1), pp.S93-S109.

Burkhardt, J.J., Heath, G.A. and Turchi, C.S., 2011. Life cycle assessment of a parabolic trough concentrating solar power plant and the impacts of key design alternatives. Environmental science & technology,45(6), pp. 2457-2464.

Bukhary, S., Chen, C., Kalra, A. and Ahmad, S., 2014. Improving Streamflow Reconstructions Using Oceanic-Atmospheric Climate Variability. In *World Environmental and Water Resources Congress 2014* (pp. 846-855).

Bukhary, S., Kalra, A. and Ahmad, S., 2015. Insights into Reconstructing Sacramento River Flow using Tree Rings and Pacific Ocean Climate Variability. In *World Environmental and Water Resources Congress 2015* (pp. 1040-1049).

Bukhary, S., Chen, C., and Ahmad, S., 2016. Analysis of Water Availability and Use for Solar Power Production in Nevada. World Environmental and Water Resources Congress 2016: pp. 164-173.

Bukhary, S., Batista, J. and Ahmad, S., 2017a. Evaluating the Feasibility of Photovoltaic-Based Plant for Potable Water Treatment. In *World Environmental and Water Resources Congress 2017* (pp. 256-263).

Bukhary, S., Weidhaas, J., Ansari, K., Mahar, R.B., Pomeroy, C., VanDerslice, J.A., Burian, S. and Ahmad, S., 2017b. Using Distributed Solar for Treatment of Drinking Water in Developing Countries. In *World Environmental and Water Resources Congress 2017* (pp. 264-276).

Bukhary, S., Ahmad, S. and Batista, J., 2018. Analyzing land and water requirements for solar deployment in the Southwestern United States. *Renewable and Sustainable Energy Reviews*, 82(3), pp. 3288-3305.

Buonocore, J.J., Luckow, P., Norris, G., Spengler, J.D., Biewald, B., Fisher, J. and Levy, J.I., 2016. Health and climate benefits of different energy-efficiency and renewable energy choices. *Nature Climate Change*, *6*(1), p.100.

Burnham, A., Han, J., Clark, C.E., Wang, M., Dunn, J.B. and Palou-Rivera, I., 2011. Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. Environmental science & technology, 46(2), pp.619-627.

Burtt, D. and Dargusch, P., 2015. The cost-effectiveness of household photovoltaic systems in reducing greenhouse gas emissions in Australia: linking subsidies with emission reductions. *Applied Energy*, *148*, pp.439-448.

Bustamante, M.L. and Gaustad, G., 2014. Challenges in assessment of clean energy supply-chains based on byproduct minerals: A case study of tellurium use in thin film photovoltaics. Applied Energy, 123, pp.397-414.

Bustamante, M. and Liao, W., 2017. A self-sustaining high-strength wastewater treatment system using solar-bio-hybrid power generation. *Bioresource Technology*, *234*, pp.415-423.

Byrne, P., Fournaison, L., Delahaye, A., Ouméziane, Y.A., Serres, L., Loulergue, P., Szymczyk, A., Mugnier, D., Malaval, J.L., Bourdais, R. and Guéguen, H., 2015. A review on the coupling of cooling, desalination and solar photovoltaic systems. *Renewable and Sustainable Energy Reviews*, *47*, pp.703-717.

California Energy Commission (CEC), 2006. Refining estimates of water-related energy use in California. *PIER Final Project Report (CEC-500-2006-118)*.

Cameron, C.P., Boyson, W.E. and Riley, D.M., 2008, May. Comparison of PV system performance-model predictions with measured PV system performance. In Photovoltaic Specialists Conference, 2008. PVSC'08. 33rd IEEE (pp. 1-6). IEEE.

Carvalho, P.C., Carvalho, L.A., Hiluy Filho, J.J. and Oliveira, R.S., 2013. Feasibility study of photovoltaic powered reverse osmosis and pumping plant configurations. IET Renewable Power Generation, 7(2), pp.134-143.

Capellán-Pérez, I., de Castro, C. and Arto, I., 2017. Assessing vulnerabilities and limits in the transition to renewable energies: Land requirements under 100% solar energy scenarios. *Renewable and Sustainable Energy Reviews*, *77*, pp.760-782.

Cassard, H., Denholm, P. and Ong, S., 2011. Technical and economic performance of residential solar water heating in the United States. Renewable and Sustainable Energy Reviews, 15(8), pp.3789-3800.

Castellanos, S., Sunter, D. and Kammen, D., 2017. Rooftop solar photovoltaic potential in cities: how scalable are assessment approaches?. *Environmental Research Letters*

Cayan, D.R., Dettinger, M.D., Pierce, D., Das, T., Knowles, N., Ralph, F.M. and Sumargo, E., 2016. Natural variability, anthropogenic climate change, and impacts on water availability and flood extremes in the Western United States. Water Policy and Planning in a Variable and Changing Climate, pp.17-42.

Cevallos-Sierra, J. and Ramos-Martin, J., 2018. Spatial assessment of the potential of renewable energy: The case of Ecuador. *Renewable and Sustainable Energy Reviews*, *81*, pp.1154-1165.

Chae, K.J. and Kang, J., 2013. Estimating the energy independence of a municipal wastewater treatment plant incorporating green energy resources. Energy Conversion and Management, 75, pp.664-672.

Chang, J., Lee, W. and Yoon, S., 2017. Energy consumptions and associated greenhouse gas emissions in operation phases of urban water reuse systems in Korea. Journal of Cleaner Production, 141, pp.728-736.

Chapman, A.J., Tezuka, T. and McLellan, B., 2017. Renewable Energy Policy Efficacy and Sustainability: The Role of Equity in Improving Energy Policy Outcomes. In *Sustainability Through Innovation in Product Life Cycle Design* (pp. 747-763). Springer Singapore.

Chatzisideris, M.D., Espinosa, N., Laurent, A. and Krebs, F.C., 2016. Ecodesign perspectives of thin-film photovoltaic technologies: A review of life cycle assessment studies. *Solar Energy Materials and Solar Cells*, *156*, pp.2-10.

Chen, C., Ahmad, S., Kalra, A. and Xu, Z.X., 2017. A dynamic model for exploring water-resource management scenarios in an inland arid area: Shanshan County, Northwestern China. *Journal of Mountain Science*, *14*(6), pp.1039-1057.

Chen, C., Kalra, A. and Ahmad, S., 2018. Hydrologic responses to climate change using downscaled GCM data on a watershed scale. *Journal of Water and Climate Change*, p.jwc2018147.

Chen, B., Han, M.Y., Peng, K., Zhou, S.L., Shao, L., Wu, X.F., Wei, W.D., Liu, S.Y., Li, Z., Li, J.S. and Chen, G.Q., 2018. Global land-water nexus: Agricultural land and freshwater use embodied in worldwide supply chains. *Science of the Total Environment*, *613*, pp.931-943.

Cheng, V.K. and Hammond, G.P., 2017. Life-cycle energy densities and land-take requirements of various power generators: A UK perspective. *Journal of the Energy Institute*, *90*(2), pp.201-213.

Chi, K.C., Nuttall, W.J. and Reiner, D.M., 2009. Dynamics of the UK natural gas industry: System dynamics modelling and long-term energy policy analysis. Technological Forecasting and Social Change, 76(3), pp. 339-357.

Cho, K., Qu, Y., Kwon, D., Zhang, H., Cid, C.A., Aryanfar, A. and Hoffmann, M.R., 2014. Effects of anodic potential and chloride ion on overall reactivity in electrochemical reactors designed for solar-powered wastewater treatment. *Environmental science & technology*, *48*(4), pp.2377-2384.

Choubin, B., Khalighi-Sigaroodi, S., Malekian, A., Ahmad, S., & Attarod, P. (2014). Drought forecasting in a semi-arid watershed using climate signals: a neuro-fuzzy modeling approach. *Journal of Mountain Science*, *11*(6), 1593-1605.

Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M. and Stahle, D.W., 2004. Long-term aridity changes in the western United States. Science,306(5698), pp.1015-1018.

Costa, S.C., Diniz, A.S.A. and Kazmerski, L.L., 2016. Dust and soiling issues and impacts relating to solar energy systems: Literature review update for 2012–2015. Renewable and Sustainable Energy Reviews, 63, pp.33-61.

Crittenden, J.C., Trussell, R.R., Hand, D.W., Howe, K.J. and Tchobanoglous, G., 2005. MWH's water treatment: principles and design. John Wiley & Sons.

Crittenden, J.C., Trussell, R.R., Hand, D.W., Howe, K.J. and Tchobanoglous, G., 2012. MWH's water treatment: principles and design. John Wiley & Sons.

Dai, J., Wu, S., Han, G., Weinberg, J., Xie, X., Wu, X., Song, X., Jia, B., Xue, W. and Yang, Q., 2017. Water-energy nexus: A review of methods and tools for macro-assessment. *Applied Energy*.

Dale, M. and Benson, S.M., 2013. Energy balance of the global photovoltaic (PV) industry-is the PV industry a net electricity producer?. Environmental science and technology, 47(7), pp. 3482-3489.

Darwish, M.A., Abdulrahim, H.K., Hassan, A.S. and Mabrouk, A.A., 2016. PV and CSP solar technologies & desalination: economic analysis. *Desalination and Water Treatment*, *57*(36), pp.16679-16702.

Dawadi, S. and Ahmad, S., 2012. Changing climatic conditions in the Colorado River Basin: implications for water resources management. *Journal of Hydrology*, *430*, pp.127-141.

Dawadi, S. and Ahmad, S., 2013. Evaluating the impact of demand-side management on water resources under changing climatic conditions and increasing population. *Journal of environmental management*, *114*, pp.261-275.

del Carmen Torres-Sibille, A., Cloquell-Ballester, V.A., Cloquell-Ballester, V.A. and Ramírez, M.Á.A., 2009. Aesthetic impact assessment of solar power plants: An objective and a subjective approach. Renewable and Sustainable Energy Reviews, 13(5), pp.986-999.

del Río, P., Resch, G., Ortner, A., Liebmann, L., Busch, S. and Panzer, C., 2017. A techno-economic analysis of EU renewable electricity policy pathways in 2030. *Energy Policy*, *104*, pp.484-493.

Denholm, P. and Kulcinski, G.L., 2004. Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. Energy Conversion and Management, 45(13), pp.2153-2172.

Denholm, P., Margolis, R.M. and Drury, E., 2009. The solar deployment system (SolarDS) model: Documentation and sample results. National Renewable Energy Laboratory.

Denholm, P. and Margolis, R.M., 2008. Land-use requirements and the per-capita solar footprint for photovoltaic generation in the United States. Energy Policy, 36(9), pp. 3531-3543.

Dobos, A., Neises, T. and Wagner, M., 2014. Advances in CSP simulation technology in the System Advisor Model. Energy Procedia, 49, pp.2482-2489.

Doubleday, K., Choi, B., Maksimovic, D., Deline, C. and Olalla, C., 2016. Recovery of inter-row shading losses using differential power-processing submodule DC–DC converters. *Solar Energy*, *135*, pp.512-517.

DSIRE, 2016. Database of State Incentives for Renewables & Efficiency. http://www.dsireusa.org/ (accessed 3 April 2016).

DSIRE, 2017. Database of State Incentives for Renewables & Efficiency (DSIRE). http://www.dsireusa.org/ (accessed 16 August 2017)

Dyson, M.E., Borgeson, S.D., Tabone, M.D. and Callaway, D.S., 2014. Using smart meter data to estimate demand response potential, with application to solar energy integration. Energy Policy, 73, pp. 607-619.

Edalat, M.M. and Stephen, H., 2017. Effects of two utility-scale solar energy plants on land-cover patterns using SMA of Thematic Mapper data. *Renewable and Sustainable Energy Reviews*, *67*, pp.1139-1152.

Elías-Maxil, J.A., van der Hoek, J.P., Hofman, J. and Rietveld, L., 2014. Energy in the urban water cycle: Actions to reduce the total expenditure of fossil fuels with emphasis on heat reclamation from urban water. Renewable and Sustainable Energy Reviews, 30, pp.808-820.

Fahrenbruch, A. and Bube, R., 2012. *Fundamentals of solar cells: photovoltaic solar energy conversion*. Elsevier.

Fang, D. and Chen, B., 2017. Linkage analysis for the water–energy nexus of city. *Applied Energy*, *189*, pp.770-779.

Feng, Y.Y., Chen, S.Q. and Zhang, L.X., 2013. System dynamics modeling for urban energy consumption and CO 2 emissions: a case study of Beijing, China. Ecological Modelling, 252, pp. 44-52.

Ferreira, A., Kunh, S.S., Fagnani, K.C., De Souza, T.A., Tonezer, C., Dos Santos, G.R. and Coimbra-Araújo, C.H., 2018. Economic overview of the use and production of photovoltaic solar energy in brazil. *Renewable and Sustainable Energy Reviews*, *81*, pp.181-191.

Forstmeier, M., Feichter, W. and Mayer, O., 2008. Photovoltaic powered water purification—challenges and opportunities. *Desalination*, *221*(1-3), pp.23-28.

Freecleansolar, 2017a. https://www.freecleansolar.com/Solar-Panel-305-Watt-Helios-7T2-305-p/7t2-305.htm (accessed 28 August 2017)

Freecleansolar , 2017b. http://www.freecleansolar.com/230W-PV-module-Solarland-SLP230-60-poly-p/slp230-60.htm (accessed 4 January 2017)

Freeman, J., Whitmore, J., Kaffine, L., Blair, N. and Dobos, A., 2013. System advisor model: Flat plate photovoltaic performance modeling validation report. National Renewable Energy Lab., Golden, CO (US).

Frisvold, G.B. and Marquez, T., 2013. Water Requirements for Large-Scale Solar Energy Projects in the West. Journal of Contemporary Water Research & Education, 151(1), pp. 106-116.

Fthenakis, V. and Kim, H.C., 2009. Land use and electricity generation: A life-cycle analysis. Renewable and Sustainable Energy Reviews, 13(6), pp. 1465-1474.

Foley, A. and Olabi, A.G., 2017. Renewable energy technology developments, trends and policy implications that can underpin the drive for global climate change. *Renewable and Sustainable Energy Reviews*, 68 (2), pp. 1112-1114

Force, J.T., 1998. Design of Munnicipal Wastewater Treatment Plants: WEF Manual of Practice No. 8. *Alexandria, Water Environment Federation*

Forrester, J.W., 2007. System dynamics—the next fifty years. System Dynamics Review, 23(2-3), pp. 359-370.

Forrester, J.W., 2003. Dynamic models of economic systems and industrial organizations. System Dynamics Review, 19(4), p. 329.

Forrester, J.W., 1987. Lessons from system dynamics modeling. System Dynamics Review, 3(2), pp. 136-149.

Forrester, J.W., 1960. The impact of feedback control concepts on the management sciences. Foundation for Instrumentation Education and Research.

Forrester, J.W., 1958. Industrial dynamics: a major breakthrough for decision makers. Harvard business review, 36(4), pp. 37-66.

Fu, R., Chung, D., Lowder, T., Feldman, D., Ardani, K. and Margolis, R., 2016. US Solar Photovoltaic System Cost Benchmark: Q1 2016. *National Renewable Energy Laboratory, US Department of Energy. NREL/TP-6A20-66532*.

Fu, R., Feldman, D.J., Margolis, R.M., Woodhouse, M.A. and Ardani, K.B., 2017. *US solar photovoltaic system cost benchmark: Q1 2017* (No. NREL/TP-6A20-68925). National Renewable Energy Laboratory (NREL), Golden, CO (United States).

Gagnon, P., Margolis, R., Melius, J., Phillips, C. and Elmore, R., 2016. *Rooftop solar photovoltaic technical potential in the United States: A detailed assessment*. National Renewable Energy Laboratory.

García-García, A., Martínez-Miranda, V., Martínez-Cienfuegos, I.G., Almazán-Sánchez, P.T., Castañeda-Juárez, M. and Linares-Hernández, I., 2015. Industrial wastewater treatment by electrocoagulation–electrooxidation processes powered by solar cells. *Fuel, 149,* pp.46-54.

García-Vaquero, N., Lee, E., Castañeda, R.J., Cho, J. and López-Ramírez, J.A., 2014. Comparison of drinking water pollutant removal using a nanofiltration pilot plant powered by renewable energy and a conventional treatment facility. Desalination, 347, pp.94-102.

Garfin, G., Franco, G., Blanco, H., Comrie, A., Gonzalez, P., Piechota, T., Smyth, R. and Waskom, R., 2014. Southwest. In US Global Change Research Program.

Garg, M.C. and Joshi, H., 2015. A Review on PV-RO Process: Solution to Drinking Water Scarcity due to High Salinity in Non-Electrified Rural Areas. Separation Science and Technology, 50(8), pp.1270-1283.

Ghaffour, N., Lattemann, S., Missimer, T., Ng, K.C., Sinha, S. and Amy, G., 2014. Renewable energy-driven innovative energy-efficient desalination technologies. *Applied Energy*, *136*, pp.1155-1165.

Ghaffour, N., Missimer, T.M. and Amy, G.L., 2013. Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability. Desalination, 309, pp.197-207.

Ghazi, S., Sayigh, A. and Ip, K., 2014. Dust effect on flat surfaces–A review paper. Renewable and Sustainable Energy Reviews, 33, pp.742-751.

Gikas, P. and Tsoutsos, T., 2015. Near zero energy wastewater treatment plants for the Greek islands. *Desalination and Water Treatment*, *53*(12), pp.3328-3334.

Gil-Carrera, L., Escapa, A., Moreno, R. and Morán, A., 2013. Reduced energy consumption during low strength domestic wastewater treatment in a semi-pilot tubular microbial electrolysis cell. *Journal of environmental management*, *122*, pp.1-7.

Gill, A.R., Viswanathan, K.K. and Hassan, S., 2017. A test of environmental Kuznets curve (EKC) for carbon emission and potential of renewable energy to reduce green houses gases (GHG) in Malaysia. *Environment, Development and Sustainability*, pp.1-12.

Gilman, P., Blair, N., Mehos, M., Christensen, C., Janzou, S. and Cameron, C., 2008. Solar advisor model user guide for version 2.0. National Renewable Energy Laboratory, Golden, CO, Technical Report No. NREL/TP-670-43704.

Gillette, D.A., 1981. Production of dust that may be carried great distances. Geological Society of America Special Papers, 186, pp.11-26.

Gillette, D.A., Adams, J., Endo, A., Smith, D. and Kihl, R., 1980. Threshold velocities for input of soil particles into the air by desert soils. Journal of Geophysical Research: Oceans, 85(C10), pp.5621-5630.

Gilman, P. and Dobos, A., 2012. System Advisor Model, SAM 2011.12. 2: General Description (No. NREL/TP-6A20-53437). National Renewable Energy Laboratory (NREL), Golden, CO.

Glatzmaier, G., 2011. Summary Report for Concentrating Solar Power Thermal Storage Workshop: New Concepts and Materials for Thermal Energy Storage and Heat-Transfer Fluids, May 20, 2011 (No. NREL/TP-5500-52134). National Renewable Energy Laboratory (NREL), Golden, CO.

Gleeson, T., VanderSteen, J., Sophocleous, M.A., Taniguchi, M., Alley, W.M., Allen, D.M. and Zhou, Y., 2010. Groundwater sustainability strategies.Nature Geoscience, 3(6), pp. 378-379.

Gohari, A., Mirchi, A. and Madani, K., 2017. System Dynamics Evaluation of Climate Change Adaptation Strategies for Water Resources Management in Central Iran. *Water Resources Management*, *31*(5), pp.1413-1434.

Goldstein, R. and Smith, W., 2002. Water & sustainability (volume 4): US electricity consumption for water supply & treatment-the next half century. Electric Power Research Institute.

Good, J. and Johnson, J.X., 2016. Impact of inverter loading ratio on solar photovoltaic system performance. Applied Energy, 177, pp.475-486.

Grainger, A., 2013. The threatening desert: controlling desertification. Routledge.

Green, M.A., Emery, K., Hishikawa, Y., Warta, W. and Dunlop, E.D., 2015. Solar cell efficiency tables (Version 45). Progress in photovoltaics: research and applications, 23(1), pp.1-9.

Green, M.A. and Bremner, S.P., 2017. Energy conversion approaches and materials for high-efficiency photovoltaics. *Nature materials*, *16*(1), pp.23-34.

Green, M.A., Hishikawa, Y., Warta, W., Dunlop, E.D., Levi, D.H., Hohl-Ebinger, J. and Ho-Baillie, A.W., 2017. Solar cell efficiency tables (version 50). *Progress in Photovoltaics: Research and Applications*, *25*(7), pp.668-676.

Greenblatt, J.B., 2015. Modeling California policy impacts on greenhouse gas emissions. Energy Policy, 78, pp. 158-172.

Gormus, N.A., Soytas, U. and Diltz, J.D., 2015. Oil Prices, Fossil-Fuel Stocks and Alternative Energy Stocks. International Journal of Economics and Finance, 7(7), p. 43.

Gude, V.G., 2015. Energy and water autarky of wastewater treatment and power generation systems. *Renewable and sustainable energy reviews*, *45*, pp.52-68.

Hadian, S. and Madani, K., 2013. The water demand of energy: implications for sustainable energy policy development. Sustainability, 5(11), pp. 4674-4687.

Hagerman, S., Jaramillo, P. and Morgan, M.G., 2016. Is rooftop solar PV at socket parity without subsidies?. *Energy Policy*, *89*, pp.84-94.

Haegermark, M., Kovacs, P. and Dalenbäck, J.O., 2017. Economic feasibility of solar photovoltaic rooftop systems in a complex setting: a Swedish case study. *Energy*, *127*, pp.18-29.

Haines, A., McMichael, A.J., Smith, K.R., Roberts, I., Woodcock, J., Markandya, A., Armstrong, B.G., Campbell-Lendrum, D., Dangour, A.D., Davies, M. and Bruce, N., 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers. *The Lancet*, *374*(9707), pp.2104-2114.

Halder, P.K., 2016. Potential and economic feasibility of solar home systems implementation in Bangladesh. *Renewable and Sustainable Energy Reviews*, *65*, pp.568-576.

Hammad, B., Al-Sardeah, A., Al-Abed, M., Nijmeh, S. and Al-Ghandoor, A., 2017. Performance and economic comparison of fixed and tracking photovoltaic systems in Jordan. *Renewable and Sustainable Energy Reviews*, *80*, pp.827-839.

Hamiche, A.M., Stambouli, A.B. and Flazi, S., 2016. A review of the water-energy nexus. Renewable and Sustainable Energy Reviews, 65, pp.319-331.

Han, C., Liu, J., Liang, H., Guo, X. and Li, L., 2013. An innovative integrated system utilizing solar energy as power for the treatment of decentralized wastewater. *Journal of environmental sciences*, *25*(2), pp.274-279.

Harto, C., Meyers, R. and Williams, E., 2010. Life cycle water use of low-carbon transport fuels. *Energy Policy*, *38*(9), pp.4933-4944

Hendricks, D.W., 2006. *Water treatment unit processes: physical and chemical*. CRC press.

Hendricks, D.W., 2016. *Water treatment unit processes: physical and chemical*. CRC press.

Hernandez, R.R., Easter, S.B., Murphy-Mariscal, M.L., Maestre, F.T., Tavassoli, M., Allen, E.B., Barrows, C.W., Belnap, J., Ochoa-Hueso, R., Ravi, S. and Allen, M.F., 2014. Environmental impacts of utility-scale solar energy. Renewable and Sustainable Energy Reviews, 29, pp. 766-779.

Hernández-Moro, J. and Martínez-Duart, J.M., 2013. Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution. Renewable and Sustainable Energy Reviews, 20, pp.119-132

Hoel, M. and Kverndokk, S., 1996. Depletion of fossil fuels and the impacts of global warming. Resource and energy economics, 18(2), pp.115-136.

Horner, R.M. and Clark, C.E., 2013. Characterizing variability and reducing uncertainty in estimates of solar land use energy intensity. *Renewable and Sustainable Energy Reviews*, *23*, pp.129-137.

Houari, Y., Speirs, J., Candelise, C. and Gross, R., 2014. A system dynamics model of tellurium availability for CdTe PV. Progress in Photovoltaics: Research and Applications, 22(1), pp. 129-146.

Howells, M., Hermann, S., Welsch, M., Bazilian, M., Segerström, R., Alfstad, T., Gielen, D., Rogner, H., Fischer, G., Van Velthuizen, H. and Wiberg, D., 2013. Integrated analysis of climate change, land-use, energy and water strategies. *Nature Climate Change*, *3*(7), pp.621-626.

Hsu, D.D., O'Donoughue, P., Fthenakis, V., Heath, G.A., Kim, H.C., Sawyer, P., Choi, J.K. and Turney, D.E., 2012. Life cycle greenhouse gas emissions of crystalline silicon photovoltaic electricity generation. Journal of Industrial Ecology, 16(s1), pp. S122-S135.

Huang, W., Ma, D. and Chen, W., 2017. Connecting water and energy: assessing the impacts of carbon and water constraints on China's power sector. *Applied Energy*, *185*, pp.1497-1505.

Huggins, T., Fallgren, P.H., Jin, S. and Ren, Z.J., 2013. Energy and performance comparison of microbial fuel cell and conventional aeration treating of wastewater. *J. Microb. Biochem. Technol. S*, *6*(2).

Hussey, K. and Pittock, J., 2012. The energy–water nexus: Managing the links between energy and water for a sustainable future. *Ecology and Society*, *17*(1).

Invertersupply, 2017. https://www.invertersupply.com/index.php?main_page=product_info&products_id=3037&gclid=EAIaIQobChMI48We7_3L2AIViGp-Ch340wUQEAkYAiABEgLFxPD_BwE (accessed 11 January 2017)

IPCC, 2014. Intergovernmental Panel on Climate Change. Climate Change 2014–Impacts, Adaptation and Vulnerability: Regional Aspects. Cambridge University Press.

Jardine, A., Merideth, R., Black, M. and LeRoy, S., 2013. Assessment of climate change in the southwest United States: a report prepared for the National Climate Assessment. Island press.

Jeon, C. and Shin, J., 2014. Long-term renewable energy technology valuation using system dynamics and Monte Carlo simulation: Photovoltaic technology case. Energy, 66, pp. 447-457.

Jones-Albertus, R., Feldman, D., Fu, R., Horowitz, K. and Woodhouse, M., 2016. Technology advances needed for photovoltaics to achieve widespread grid price parity. Progress in Photovoltaics: Research and Applications.

Jones, M.A., Odeh, I., Haddad, M., Mohammad, A.H. and Quinn, J.C., 2016. Economic analysis of photovoltaic (PV) powered water pumping and desalination without energy storage for agriculture. Desalination, 387, pp.35-45.

Kalogirou, S.A., 2013a. *Solar energy engineering: processes and systems*. Academic Press.

Kalogirou, S.A., 2013b. Solar thermoelectric power generation in Cyprus: Selection of the best system. *Renewable energy*, *49*, pp.278-281.

Kalra, A., Sagarika, S., Pathak, P. and Ahmad, S., 2017. Hydro-climatological changes in the Colorado River Basin over a century. Hydrological Sciences Journal, 62(14), pp.2280-2296.

Kammen, D.M. and Sunter, D.A., 2016. City-integrated renewable energy for urban sustainability. *Science*, *352*(6288), pp.922-928.

Kang, M.H., Kim, N., Yun, C., Kim, Y.H., Rohatgi, A. and Han, S.T., 2017. Analysis of a commercial-scale photovoltaics system performance and economic feasibility. *Journal of Renewable and Sustainable Energy*, *9*(2), p.023505.

Kang, M.H. and Rohatgi, A., 2016. Quantitative analysis of the levelized cost of electricity of commercial scale photovoltaics systems in the US. Solar Energy Materials and Solar Cells, 154, pp.71-77.

Kavvada, O., Horvath, A., Stokes-Draut, J.R., Hendrickson, T.P., Eisenstein, W.A. and Nelson, K.L., 2016. Assessing Location and Scale of Urban Nonpotable Water Reuse Systems for Life-Cycle Energy Consumption and Greenhouse Gas Emissions. Environmental science & technology, 50(24), pp.13184-13194.

Kawamura, S., 1991. Integrated Design of Water Treatment Facilities. New York: John Willey and Sons.

Kenney, D.S. and Wilkinson, R. eds., 2011. The water-energy nexus in the American West. Edward Elgar Publishing.

Khalid, A.M., Mitra, I., Warmuth, W. and Schacht, V., 2016. Performance ratio–Crucial parameter for grid connected PV plants. Renewable and Sustainable Energy Reviews, 65, pp.1139-1158.

Khan, J. and Arsalan, M.H., 2016. Solar power technologies for sustainable electricity generation–A review. Renewable and Sustainable Energy Reviews, 55, pp.414-425.

Khanzada, N.K., Khan, S.J. and Davies, P.A., 2017. Performance evaluation of reverse osmosis (RO) pre-treatment technologies for in-land brackish water treatment. *Desalination*, *406*, pp.44-50.

Kim, H.C., Fthenakis, V., Choi, J.K. and Turney, D.E., 2012. Life cycle greenhouse gas emissions of thin-film photovoltaic electricity generation.Journal of Industrial Ecology, 16(s1), pp. S110-S121.

Kittner, N., Lill, F. and Kammen, D.M., 2017. Energy storage deployment and innovation for the clean energy transition. *Nature Energy*, *2*(9), p.nenergy2017125

Klein, G., Krebs, M., Hall, V., O'Brien, T. and Blevins, B.B., 2005. California's water-energy relationship. California Energy Commission

Klise, G.T., Tidwell, V.C., Reno, M.D., Moreland, B.D., Zemlick, K.M. and Macknick, J., 2013. Water use and supply concerns for utility-scale solar projects in the southwestern United States. SAND2013-5238. Sandia National Laboratories.

Krupa, J. and Harvey, D., 2017. Renewable electricity finance in the United States: A state-of-the-art review. *Energy*.

Krzeminski, P., van der Graaf, J.H. and van Lier, J.B., 2012. Specific energy consumption of membrane bioreactor (MBR) for sewage treatment. *Water science and technology*, *65*(2), pp.380-392.

Kurokawa, K., 2014. Energy from the Desert: Feasability of Very Large Scale Power Generation (VLS-PV). Routledge.

Lai, C.S. and McCulloch, M.D., 2017. Levelized cost of electricity for solar photovoltaic and electrical energy storage. *Applied Energy*, *190*, pp.191-203.

Lauer, W., Barsotti, M.G. and Hardy, D.K., 2009. Chemical Feed Field Guide for Treatment Plant Operators. American Water Works Association.

Lawler, D.F. and Singer, P.C., 1993. Analyzing disinfection kinetics and reactor design: a conceptual approach versus the SWTR. Journal-American Water Works Association, 85(11), pp.67-76.

LBL, 2016. Lawrence Berkeley Laboratory. https://emp.lbl.gov/projects/renewables-portfolio (accessed 25 July 2016).

Lee, C.C. and Lin, S.D., 2007. *Handbook of environmental engineering calculations*. McGraw Hill.

Lee, M., Keller, A.A., Chiang, P.C., Den, W., Wang, H., Hou, C.H., Wu, J., Wang, X. and Yan, J., 2017. Water-energy nexus for urban water systems: A comparative review on energy intensity and environmental impacts in relation to global water risks. *Applied Energy*, *205*, pp.589-601.

Lenert, A. and Wang, E.N., 2012. Optimization of nanofluid volumetric receivers for solar thermal energy conversion. Solar Energy, 86(1), pp.253-265.

Lewis, N.S., 2007. Toward cost-effective solar energy use. *science*, *315*(5813), pp.798-801.

Leopold, A., 2016. Energy related system dynamic models: a literature review. Central European Journal of Operations Research, 24(1), pp. 231-261.

Li, J.S., Duan, N., Guo, S., Shao, L., Lin, C., Wang, J.H., Hou, J., Hou, Y., Meng, J. and Han, M.Y., 2012. Renewable resource for agricultural ecosystem in China: ecological benefit for biogas by-product for planting.Ecological Informatics, 12, pp. 101-110.

Lin, B. and Ahmad, I., 2017. Analysis of energy related carbon dioxide emission and reduction potential in Pakistan. *Journal of Cleaner Production*, *143*, pp.278-287.

Linssen, J., Stenzel, P. and Fleer, J., 2017. Techno-economic analysis of photovoltaic battery systems and the influence of different consumer load profiles. *Applied Energy*, *185*, pp.2019-2025.

Liu, D.H. and Liptak, B.G., 1999. *Environmental Engineers' Handbook on CD-ROM*. CRC press.

Liu, J., Mao, G., Hoekstra, A.Y., Wang, H., Wang, J., Zheng, C., van Vliet, M.T., Wu, M., Ruddell, B. and Yan, J., 2017. Managing the energy-water-food nexus for sustainable development.

Liu, R.S., 2016. *Phosphors, Up Conversion Nano Particles, Quantum Dots and Their Applications* (Vol. 1). Springer.

Liu, X. and Zeng, M., 2017. Renewable energy investment risk evaluation model based on system dynamics. *Renewable and Sustainable Energy Reviews*, *73*, pp.782-788.

Loizidou, M., Moustakas, K., Malamis, D., Rusan, M. and Haralambous, K.J., 2015. Development of a decentralized innovative brackish water treatment unit for the production of drinking water. Desalination and Water Treatment, 53(12), pp.3187-3198.

Loonen, E., Pruyt, E. and Hamarat, C., 2013, July. Exploring carbon futures in the EU power sector: Using Exploratory System Dynamics Modelling and Analysis to explore policy regimes under deep uncertainty. In Proceedings of the 31st International Conference of the System Dynamics Society, Cambridge, USA, 21-25 July 2013. System Dynamics Society.

López-Herraiz, M., Fernández, A.B., Martinez, N. and Gallas, M., 2017. Effect of the optical properties of the coating of a concentrated solar power central receiver on its thermal efficiency. Solar Energy Materials and Solar Cells, 159, pp.66-72

Ma, Z., Mehos, M., Glatzmaier, G. and Sakadjian, B.B., 2015. Development of a concentrating solar power system using fluidized-bed technology for thermal energy conversion and solid particles for thermal energy storage. Energy Procedia, 69, pp.1349-1359.

Ma, S., Xu, Y.P., Li, X.F., Wang, Y.F., Zhang, N. and Xu, Y.R., 2017. Research on Reduction of Solar Power Curtailment with Grid Connected Energy Storage System Based on Time-Series Production Simulation. *Energy and Power Engineering*, *9*(04), p.162.

Maammeur, H., Hamidat, A., Loukarfi, L., Missoum, M., Abdeladim, K. and Nacer, T., 2017. Performance investigation of grid-connected PV systems for family farms: case study of North-

MacAlpine, S., Deline, C. and Dobos, A., 2017. Measured and estimated performance of a fleet of shaded photovoltaic systems with string and module-level inverters. *Progress in Photovoltaics: Research and Applications*. 25 (8), pp. 714–726

MacDonald, G.M., 2010. Water, climate change, and sustainability in the southwest. Proceedings of the National Academy of Sciences, 107(50), pp. 21256-21262.

MacDonald, A.E., Clack, C.T., Alexander, A., Dunbar, A., Wilczak, J. and Xie, Y., 2016. Future cost-competitive electricity systems and their impact on US CO2 emissions. *Nature Climate Change*, *6*(5), pp.526-531.

MacDougall, A.H. and Friedlingstein, P., 2015. The origin and limits of the near proportionality between climate warming and cumulative CO2 emissions. Journal of Climate, 28(10), pp. 4217-4230.

Macknick, J. and Cohen, S., 2015. Water Impacts of High Solar PV Electricity Penetration (No. NREL/TP-6A20-63011). NREL (National Renewable Energy Laboratory (NREL).

Macknick, J., Newmark, R., Heath, G. and Hallett, K.C., 2012a. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environmental Research Letters,7(4), p. 045802.

Macknick, J., Sattler, S., Averyt, K., Clemmer, S. and Rogers, J., 2012b. The water implications of generating electricity: water use across the United States based on different electricity pathways through 2050. Environmental Research Letters, 7(4), p. 045803.

Mahmoud, E. and El Nather, H., 2003. Renewable energy and sustainable developments in Egypt: photovoltaic water pumping in remote areas. *Applied Energy*, *74*(1), pp.141-147

Mai, T., Mulcahy, D., Hand, M.M. and Baldwin, S.F., 2014. Envisioning a renewable electricity future for the United States. *Energy*, *65*, pp.374-386.

Malagueta, D., Szklo, A., Soria, R., Dutra, R., Schaeffer, R. and Borba, B.S.M.C., 2014. Potential and impacts of Concentrated Solar Power (CSP) integration in the Brazilian electric power system. Renewable Energy, 68, pp.223-235.

Malvoni, M., Leggieri, A., Maggiotto, G., Congedo, P.M. and De Giorgi, M.G., 2017. Long term performance, losses and efficiency analysis of a 960kW P photovoltaic system in the Mediterranean climate. *Energy Conversion and Management*, *145*, pp.169-181.

Mani, M. and Pillai, R., 2010. Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations. Renewable and Sustainable Energy Reviews, 14(9), pp.3124-3131.

Marchal, V., Dellink, R., Van Vuuren, D., Clapp, C., Chateau, J., Lanzi, E., Magné, B. and van Vliet, J., 2011. OECD environmental outlook to 2050. *Organization for Economic Co-operation and Development*.

Margolis, R., Gagnon, P., Melius, J., Phillips, C. and Elmore, R., 2017. Using GIS-based methods and Lidar data to estimate rooftop solar technical potential in US cities. *Environmental Research Letters*, 12(7).

Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L. and Linsey, K.S., 2014. Estimated use of water in the United States in 2010 (No. 1405). US Geological Survey.

Mays, L.W., 2006. *Water resources engineering*. John Wiley & Sons.

Mazhari, E., Zhao, J., Celik, N., Lee, S., Son, Y.J. and Head, L., 2011. Hybrid simulation and optimization-based design and operation of integrated photovoltaic generation, storage units, and grid. Simulation Modelling Practice and Theory, 19(1), pp. 463-481.

McCabe, J., 2011. Salvage Value of Photovoltaic Systems. In World Renewable Energy Forum. Littleton, CO.

McEvoy, D.J., Huntington, J.L., Abatzoglou, J.T. and Edwards, L.M., 2012. An evaluation of multiscalar drought indices in Nevada and Eastern California. Earth Interactions, 16(18), pp.1-18.

McKinney, R.E., 2004. Environmental pollution control microbiology: a fifty-year perspective. CRC Press.

Mekonnen, M.M., Gerbens-Leenes, P.W. and Hoekstra, A.Y., 2016. Future electricity: The challenge of reducing both carbon and water footprint. Science of the total environment, 569, pp.1282-1288.

Meldrum, J., Nettles-Anderson, S., Heath, G. and Macknick, J., 2013. Life cycle water use for electricity generation: a review and harmonization of literature estimates. Environmental Research Letters, 8(1), p. 015031.

Michalena, E. and Hills, J.M. eds., 2013. *Renewable Energy Governance: Complexities and Challenges* (Vol. 23). Springer Science & Business Media.

Mileva, A., Johnston, J., Nelson, J.H. and Kammen, D.M., 2016. Power system balancing for deep decarbonization of the electricity sector. *Applied Energy*, *162*, pp.1001-1009.

Mirchi, A., Madani, K., Watkins, D. and Ahmad, S., 2012. Synthesis of system dynamics tools for holistic conceptualization of water resources problems. *Water resources management*, *26*(9), pp.2421-2442.

Mizuta, K. and Shimada, M., 2010. Benchmarking energy consumption in municipal wastewater treatment plants in Japan. *Water Science and Technology*, *62*(10), pp.2256-2262

Mekonnen, M.M., Gerbens-Leenes, P.W. and Hoekstra, A.Y., 2016. Future electricity: The challenge of reducing both carbon and water footprint. Science of the total environment, 569, pp.1282-1288.

Mohammed, Y.S., Mustafa, M.W., Bashir, N. and Ibrahem, I.S., 2017. Existing and recommended renewable and sustainable energy development in Nigeria based on autonomous energy and microgrid technologies. *Renewable and Sustainable Energy Reviews*, *75*, pp.820-838.

Mohanty, P., Muneer, T. and Kolhe, M. eds., 2015. *Solar photovoltaic system applications: a guidebook for off-grid electrification*. Springer.

Molinos-Senante, M. and Guzmán, C., 2016. Reducing CO_2 emissions from drinking water treatment plants: A shadow price approach. *Applied Energy*.

Molinos-Senante, M. and Sala-Garrido, R., 2017. Energy intensity of treating drinking water: Understanding the influence of factors. *Applied Energy*, *202*, pp.275-281.

Moomaw, W., P. Burgherr, G. Heath, M. Lenzen, J. Nyboer, A. Verbruggen, 2011: Annex II: Methodology. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Morales, T.D. and Busch, J., 2010. Design of Small Photovoltaic (PV) Solar-Powered Water Pump Systems. Portland, Oregon.

Moumouni, Y., Ahmad, S. and Baker, R.J., 2014. A system dynamics model for energy planning in Niger. *Int. J. Energy Power Eng*, *3*(6), p.308.

Mulroy, P., 2017. *The Water Problem: Climate Change and Water Policy in the United States*. Brookings Institution Press.

Mundada, A.S., Prehoda, E.W. and Pearce, J.M., 2017. US market for solar photovoltaic plug-and-play systems. *Renewable Energy*, *103*, pp.255-264.

Mundada, A.S., Shah, K.K. and Pearce, J.M., 2016. Levelized cost of electricity for solar photovoltaic, battery and cogen hybrid systems. *Renewable and Sustainable Energy Reviews*, *57*, pp.692-703.

Munoz, F.D., Pumarino, B.J. and Salas, I.A., 2017. Aiming Low and Achieving It: A Long-Term Analysis of a Renewable Policy in Chile. *Energy Economics*.

Murphy, D.J., O'Connor, B.L., Mayhorn, D.T., Almer, L.I., Bowen, E.E., White, E.M. and Kim, C., 2014. Alternative water resources for utility-scale solar energy development. *Energy Procedia*, *49*, pp.2501-2511.

Musi, R., Grange, B., Sgouridis, S., Guedez, R., Armstrong, P., Slocum, A. and Calvet, N., 2017, June. Techno-economic analysis of concentrated solar power plants in terms of levelized cost of electricity. In *AIP Conference Proceedings* (Vol. 1850, No. 1, p. 160018). AIP Publishing.

Naill, R.F., 1992. A system dynamics model for national energy policy planning. System Dynamics Review, 8(1), pp. 1-19.

Nanduri, V. and Saavedra-Antolínez, I., 2013. A competitive Markov decision process model for the energy–water–climate change nexus. *Applied energy*, *111*, pp.186-198.

National Grid, (2018). https://www.nationalgridus.com/MA-Home/Default (accessed 2 February 2018)

Nemet, G.F., O'Shaughnessy, E., Wiser, R., Darghouth, N.R., Barbose, G., Gillingham, K. and Rai, V., 2017. What factors affect the prices of low-priced US solar PV systems?. *Renewable Energy*, *114*, pp.1333-1339.

Newell, T.S., 2012. The Impact of Advanced Wastewater Treatment Technologies and Wastewater Strength on the Energy Consumption of Large Wastewater Treatment Plants.

Nonhebel, S., 2005. Renewable energy and food supply: will there be enough land?. Renewable and sustainable energy reviews, 9(2), pp. 191-201.

Noorollahi, E., Fadai, D., Akbarpour Shirazi, M. and Ghodsipour, S.H., 2016. Land Suitability Analysis for Solar Farms Exploitation Using GIS and Fuzzy Analytic Hierarchy Process (FAHP)—A Case Study of Iran. *Energies*, *9*(8), p.643.

NREL, 2016. National Renewable Energy Laboratory (NREL). http://www.nrel.gov/pv/ (accessed 22 November 2016).

NREL, 2017. National Renewable Energy Laboratory (NREL). http://www.nrel.gov/pv/ (accessed 5 November 2017).

Ntsoane, M., 2017. *Rooftop solar PV potential assessment in the City of Johannesburg* (Doctoral dissertation, Stellenbosch: Stellenbosch University.

Nugent, D. and Sovacool, B.K., 2014. Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. *Energy Policy*, *65*, pp.229-244.

Nussbaum, E. M., Owens, M. C., Sinatra, G. M., Rehmat, A. P., Cordova, J. R., Ahmad, S.,and Dascalu, S. M. (2015). Losing the Lake: Simulations to Promote Gains in Student Knowledge and Interest about Climate Change. *International Journal of Environmental and Science Education*, *10*(6), 789-811.

Nykvist, B. and Nilsson, M., 2015. Rapidly falling costs of battery packs for electric vehicles. *Nature Climate Change*, *5*(4), pp.329-332.

NYSERDA, 2016. New York State Energy Research and Development Authority. http://www.nyserda.ny.gov/All-Programs/Programs/Main-Tier/History (accessed 24 August 2016).

Okoye, C.O. and Oranekwu-Okoye, B.C., 2017. Economic feasibility of solar PV system for rural electrification in Sub-Sahara Africa. *Renewable and Sustainable Energy Reviews*.

Oliveira, C.T., Antonio, F., Burani, G.F. and Udaeta, M.E.M., 2017. GHG reduction and energy efficiency analyses in a zero-energy solar house archetype. *International Journal of Low-Carbon Technologies*, *12*(3), pp.225-232.

Olsson, G., 2015. Water and energy: threats and opportunities. Iwa Publishing.

Omar, M.A. and Mahmoud, M.M., 2017. Grid connected PV-home systems in Palestine: A review on technical performance, effects and economic feasibility. *Renewable and Sustainable Energy Reviews*.

Ong, S., Campbell, C., Denholm, P., Margolis, R. and Heath, G., 2013. Land-use requirements for solar power plants in the United States. Golden, CO: National Renewable Energy Laboratory.

Ozoegwu, C.G., Mgbemene, C.A. and Ozor, P.A., 2017. The status of solar energy integration and policy in Nigeria. Renewable and Sustainable Energy Reviews, 70, pp.457-471.

Panepinto, D., Fiore, S., Zappone, M., Genon, G. and Meucci, L., 2016. Evaluation of the energy efficiency of a large wastewater treatment plant in Italy. *Applied Energy*, *161*, pp.404-411.

Pathak P, Kalra A, and Ahmad S (2016a) Temperature and Precipitation changes in the Midwestern United States: Implications for water management, International Journal of Water Resources Development, 10.1080/07900627.2016.1238343.

Pathak, P., Kalra, A., Ahmad, S., & Bernardez, M. (2016b). Wavelet-aided analysis to estimate seasonal variability and dominant periodicities in temperature, precipitation, and streamflow in the Midwestern United States. Water resources management, 30(13), 4649-4665.

Pathak P, Kalra A, Lamb KW, Miller WP, Ahmad S, Amerineni, R. and Ponugoti, D. P. (2017) Climatic variability of the Pacific and Atlantic Oceans and western US snowpack, International Journal of Climatology, DOI: 10.1002/joc.5241

Paz, A., Maheshwari, P., Kachroo, P. and Ahmad, S., 2013. Estimation of performance indices for the planning of sustainable transportation systems. *Advances in Fuzzy Systems*, *2013*, p.2.

Pearce, D.W. and R.K. Turner, 1990, Economics of natural resources and the environment (Harvester Wheatsbeaf, London).

Pichel, N., Vivar, M. and Fuentes, M., 2016. Performance analysis of a solar photovoltaic hybrid system for electricity generation and simultaneous water disinfection of wild bacteria strains. *Applied Energy*, *171*, pp.103-112.

Pierce, W., Gauché, P., von Backström, T., Brent, A.C. and Tadros, A., 2013. A comparison of solar aided power generation (SAPG) and stand-alone concentrating solar power (CSP): A South African case study. Applied Thermal Engineering, 61(2), pp.657-662.

Pirnie, M., and Yonkin, M., 2008. Statewide assessment of energy use by the municipal water and wastewater sector. New York State Energy Research and Development. Authority (NYSERDA), Report, pp.08-17.

Pilli-Sihvola, K., Aatola, P., Ollikainen, M. and Tuomenvirta, H., 2010. Climate change and electricity consumption—Witnessing increasing or decreasing use and costs? Energy Policy, 38(5), pp. 2409-2419.

Plappally, A.K., and Lienhard V, J.H., 2012. Energy requirements for water production, treatment, end use, reclamation, and disposal. Renewable and Sustainable Energy Reviews, 16(7), pp.4818-4848.

Polman, A., Knight, M., Garnett, E.C., Ehrler, B. and Sinke, W.C., 2016. Photovoltaic materials: Present efficiencies and future challenges. *Science*, *352*(6283), p.aad4424.

Prabhakara, C. and Dalu, G., 1976. Remote sensing of the surface emissivity at 9 μm over the globe. Journal of Geophysical Research, 81(21), pp. 3719-3724.

Prashar, D. and Ahmad, S., 2010. Evaluating Conservation Potential in Agricultural and Municipal Water Use in South Florida. In *World Environmental and Water Resources Congress 2010: Challenges of Change* (pp. 2572-2583).

Prehoda, E.W. and Pearce, J.M., 2017. Potential lives saved by replacing coal with solar photovoltaic electricity production in the US. *Renewable and Sustainable Energy Reviews*, *80*, pp.710-715.

Prieto, C., Miró, L., Peiró, G., Oró, E., Gil, A. and Cabeza, L.F., 2016. Temperature distribution and heat losses in molten salts tanks for CSP plants. Solar Energy, 135, pp.518-526.

Rakness, K.L., 2005. *Ozone in drinking water treatment: process design, operation, and optimization*. American Water Works Association.

Reheis, M.C., 1997. Dust deposition downwind of Owens (dry) Lake, 1991–1994: Preliminary findings. Journal of Geophysical Research: Atmospheres, 102(D22), pp.25999-26008.

Richards, B.S., Shen, J. and Schäfer, A.I., 2017. Water–Energy Nexus Perspectives in the Context of Photovoltaic-Powered Decentralized Water Treatment Systems: A Tanzanian Case Study. *Energy Technology*.

Rock, M.T., 1998. Freshwater use, freshwater scarcity, and socioeconomic development. The Journal of Environment & Development, 7(3), pp.278-301.

Rodrigues, S., Torabikalaki, R., Faria, F., Cafôfo, N., Chen, X., Ivaki, A.R., Mata-Lima, H. and Morgado-Dias, F., 2016. Economic feasibility analysis of small scale PV systems in different countries. *Solar Energy*, *131*, pp.81-95.

Rothausen, S.G. and Conway, D., 2011. Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change*, *1*(4), pp.210-219.

Rovira, A., Barbero, R., Montes, M.J., Abbas, R. and Varela, F., 2016. Analysis and comparison of Integrated Solar Combined Cycles using parabolic troughs and linear Fresnel reflectors as concentrating systems. Applied Energy, 162, pp.990-1000.

Rusuli, Y., Li, L., Ahmad, S. and Zhao, X., 2015. Dynamics model to simulate water and salt balance of Bosten Lake in Xinjiang, China. *Environmental Earth Sciences*, *74*(3), pp.2499-2510.

Qaiser, K., Ahmad, S., Johnson, W. and Batista, J., 2011. Evaluating the impact of water conservation on fate of outdoor water use: a study in an arid region. Journal of Environmental Management, 92(8), pp. 2061-2068.

Qaiser, K., Ahmad, S., Johnson, W. and Batista, J.R., 2013. Evaluating water conservation and reuse policies using a dynamic water balance model. *Environmental management*, *51*(2), pp.449-458.

Qasim, S.R., 1998. *Wastewater treatment plants: planning, design, and operation*. CRC Press.

Qu, X., Alvarez, P.J. and Li, Q., 2013. Applications of nanotechnology in water and wastewater treatment. Water research, 47(12), pp.3931-3946.

Ramírez, F.J., Honrubia-Escribano, A., Gómez-Lázaro, E. and Pham, D.T., 2017. Combining feed-in tariffs and net-metering schemes to balance development in adoption of photovoltaic energy: Comparative economic assessment and policy implications for European countries. *Energy Policy*, *102*, pp.440-452.

Ramírez-Sagner, G., Mata-Torres, C., Pino, A. and Escobar, R.A., 2017. Economic feasibility of residential and commercial PV technology: The Chilean case. *Renewable Energy*, *111*, pp.332-343

Rashwan, S.S., Shaaban, A.M. and Al-Suliman, F., 2017. A comparative study of a small-scale solar PV power plant in Saudi Arabia. *Renewable and Sustainable Energy Reviews*, *80*, pp.313-318.

Realgoods, 2017. https://realgoods.com/sunpower-spr-4000m-4000w-inverter-240-208v (accessed 6 September 2017)

Reiter, E., Lowder, T., Mathur, S. and Mercer, M., 2016. *Virginia Solar Pathways Project. Economic Study of Utility-Administered Solar Programs: Soft Costs, Community Solar, and Tax Normalization Considerations* (No. NREL/TP-6A42-65758). NREL (National Renewable Energy Laboratory (NREL), Golden, CO (United States)).

Reynolds, T.D. and Richards, P.A., 1996. *Unit Operations and Processes in Environmental Engineering. PWS Publishing Company, Boston, USA.*

Richmond, B., Peterson, S., and Vescuso, P. (1987). An Academic User's Guide to STELLA, High Performance Systems Inc. Hanover, NH.

Robalino-López, A., Mena-Nieto, A. and García-Ramos, J.E., 2014. System dynamics modeling for renewable energy and CO 2 emissions: A case study of Ecuador. Energy for Sustainable Development, 20, pp. 11-20.

Rock, M.T., 1998. Freshwater use, freshwater scarcity, and socioeconomic development. The Journal of Environment & Development, 7(3), pp.278-301.

Rodrigues, S., Torabikalaki, R., Faria, F., Cafôfo, N., Chen, X., Ivaki, A.R., Mata-Lima, H. and Morgado-Dias, F., 2016. Economic feasibility analysis of small scale PV systems in different countries. *Solar Energy*, *131*, pp.81-95.

Sahin, O., Stewart, R.A., Giurco, D. and Porter, M.G., 2017. Renewable hydropower generation as a co-benefit of balanced urban water portfolio management and flood risk mitigation. *Renewable and Sustainable Energy Reviews*, *68*, pp.1076-1087.

Sagarika, S., Kalra, A., & Ahmad, S. (2014). Evaluating the effect of persistence on long-term trends and analyzing step changes in streamflows of the continental United States. *Journal of Hydrology*, 517, 36–53.

Sagarika, S., Kalra, A., Ahmad, S. (2015a). Interconnection between oceanic-atmospheric indices and variability in the US streamflow. *Journal of Hydrology*, 525, 724-736.

Sagarika, S., Kalra, A., Ahmad, S. (2015b). Pacific Ocean and SST and Z500 climate variability and western U.S. seasonal streamflow. *International Journal of Climatology*, doi:10.1002/joc.4442.

Sahu, B.K., 2015. A study on global solar PV energy developments and policies with special focus on the top ten solar PV power producing countries. Renewable and Sustainable Energy Reviews, 43, pp. 621-634.

Saidan, M., Albaali, A.G., Alasis, E. and Kaldellis, J.K., 2016. Experimental study on the effect of dust deposition on solar photovoltaic panels in desert environment. *Renewable Energy*, *92*, pp.499-505.

Sampaio, P.G.V. and González, M.O.A., 2017. Photovoltaic solar energy: Conceptual framework. *Renewable and Sustainable Energy Reviews*, *74*, pp.590-601.

Sanders, K.T. and Webber, M.E., 2012. Evaluating the energy consumed for water use in the United States. *Environmental Research Letters*, *7*(3), p.034034.

Sarver, T., Al-Qaraghuli, A. and Kazmerski, L.L., 2013. A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches. Renewable and Sustainable Energy Reviews, 22, pp.698-733.

Sawin, J.L., Sverrisson, F., Seyboth, K., Adib, R., Murdock, H.E., Lins, C., Brown, A., Di Domenico, S.E., Kielmanowicz, D., Williamson, L.E. and Jawahar, R., 2016. Renewables 2016 Global Status Report. Key findings. A Record Breaking Year for Renewable Energy:

New Installations, Policy Targets, Investment and Jobs. Mainstreaming renewables: guidance for policy makers.

Scanlon, B.R., Duncan, I. and Reedy, R.C., 2013. Drought and the water–energy nexus in Texas. Environmental Research Letters, 8(4), p.045033.

Schäfer, A.I., Hughes, G. and Richards, B.S., 2014. Renewable energy powered membrane technology: A leapfrog approach to rural water treatment in developing countries?. Renewable and sustainable Energy reviews, 40, pp.542-556.

Schandl, H., Hatfield-Dodds, S., Wiedmann, T., Geschke, A., Cai, Y., West, J., Newth, D., Baynes, T., Lenzen, M. and Owen, A., 2016. Decoupling global environmental pressure and economic growth: Scenarios for energy use, materials use and carbon emissions. *Journal of Cleaner Production*, *132*, pp.45-56.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N.W., Clark, D.B., Dankers, R., Eisner, S., Fekete, B.M., Colón-González, F.J. and Gosling, S.N., 2014. Multimodel assessment of water scarcity under climate change. Proceedings of the National Academy of Sciences, 111(9), pp.3245-3250.

Schmalensee, R., 2015. The future of solar energy: a personal assessment. Energy Economics, 52, pp.S142-S148.

Scully, M.O., 2010. Quantum photocell: Using quantum coherence to reduce radiative recombination and increase efficiency. *Physical review letters*, *104*(20), p.207701.

Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., et al., 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. Science, 316(5828), pp.1181-1184.

Sekar, S. and Sohngen, B., 2014. The Effects of Renewable Portfolio Standards on Carbon Intensity in the United States. Resources for the Future Discussion Paper, (pp. 14-10).

Shalaby, S.M., 2017. Reverse osmosis desalination powered by photovoltaic and solar Rankine cycle power systems: A review. *Renewable and Sustainable Energy Reviews*, *73*, pp.789-797

Shafiee, S. and Topal, E., 2009. When will fossil fuel reserves be diminished?. Energy policy, 37(1), pp.181-189.

Shahzad, M.W., Burhan, M., Ang, L. and Ng, K.C., 2017. Energy-water-environment nexus underpinning future desalination sustainability. *Desalination*, *413*, pp.52-64.

Shalaby, S.M., 2017. Reverse osmosis desalination powered by photovoltaic and solar Rankine cycle power systems: A review. *Renewable and Sustainable Energy Reviews*, *73*, pp.789-797.

Sharmina, M., Hoolohan, C., Bows-Larkin, A., Burgess, P.J., Colwill, J., Gilbert, P., Howard, D., Knox, J. and Anderson, K., 2016. A nexus perspective on competing land demands: wider lessons from a UK policy case study. *Environmental Science & Policy*, *59*, pp.74-84

Shammas, N.K. and Wang, L.K., 2007. Belt filter presses. Biosolids Treatment Processes, pp.519-539.

Shawky, H.A., Abdel Fatah, A.A., Abo ElFadl, M.M. and El-Aassar, A.H.M., 2015. Design of a small mobile PV-driven RO water desalination plant to be deployed at the northwest coast of Egypt. Desalination and Water Treatment, 55(13), pp.3755-3766.

Shih, Y.H. and Tseng, C.H., 2014. Cost-benefit analysis of sustainable energy development using life-cycle co-benefits assessment and the system dynamics approach. Applied Energy, 119, pp. 57-66.

Shindell, D.T., Lee, Y. and Faluvegi, G., 2016. Climate and health impacts of US emissions reductions consistent with 2°C. *Nature Climate Change*, *6*(5), pp.503-507.

Short, W., Packey, D.J. and Holt, T., 1995. *A manual for the economic evaluation of energy efficiency and renewable energy technologies* (No. NREL/TP--462-5173). National Renewable Energy Lab., Golden, CO (United States).

Shrestha, E., Ahmad, S., Johnson, W. and Batista, J.R., 2012. The carbon footprint of water management policy options. Energy Policy, 42, pp.201-212.

Shrestha, E., Ahmad, S., Johnson, W., Shrestha, P. and Batista, J.R., 2011. Carbon footprint of water conveyance versus desalination as alternatives to expand water supply. Desalination, 280(1), pp. 33-43.

Simonovic, S.P. and Ahmad, S., 2005. Computer-based model for flood evacuation emergency planning. Natural Hazards, 34(1), pp. 25-51.

Sinha, P., Meader, A. and de Wild-Scholten, M., 2012, June. Life cycle water usage in CdTe photovoltaics. In Photovoltaic Specialists Conference (PVSC), Volume 2, 2012 IEEE 38th (pp. 1-4). IEEE.

Skone, T.J., Littlefield, J., Eckard, R., Cooney, G. Prica, M. and Marriott, J., 2012. Role of Alternative Energy Sources: Solar Thermal Technology Assessment. DOE/NETL-2012/1532. Pittsburgh, PA, U.S. Department of Energy, National Energy Technology Laboratory (NETL): 33pp.

Smith, A.L., Stadler, L.B., Cao, L., Love, N.G., Raskin, L. and Skerlos, S.J., 2014. Navigating wastewater energy recovery strategies: a life cycle comparison of anaerobic membrane bioreactor and conventional treatment systems with anaerobic digestion. *Environmental science & technology*, *48*(10), pp.5972-5981

Solar PEIS, 2012. Final Solar Energy Development Programmatic Environmental Impact Statement. http://solareis.anl.gov/Documents/fpeis/index.cfm (accessed 15 December 2015).

Solarmapper, 2016. Solar Energy Environmental Mapper. http://solarmapper.anl.gov/ (accessed 4 September 2016).

Solarpenny, 2017. http://www.solarpenny.com/Centro-Solar-p/csb260.htm (accessed 6 September 2017).

Song, J. and Choi, Y., 2016. Analysis of the Potential for Use of Floating Photovoltaic Systems on Mine Pit Lakes: Case Study at the Ssangyong Open-Pit Limestone Mine in Korea. Energies, 9(2), p.102.

Song, J. and Choi, Y., 2015. Design of photovoltaic systems to power aerators for natural purification of acid mine drainage. Renewable Energy, 83, pp.759-766.

Soshinskaya, M., Crijns-Graus, W.H., van der Meer, J. and Guerrero, J.M., 2014. Application of a microgrid with renewables for a water treatment plant. Applied Energy, 134, pp.20-34.

Souza, F.L., Saéz, C., Llanos, J., Lanza, M.R., Cañizares, P. and Rodrigo, M.A., 2015. Solar-powered CDEO for the treatment of wastewater polluted with the herbicide 2, 4-D. *Chemical Engineering Journal*, *277*, pp.64-69.

Spellman, 2013. Water & wastewater infrastructure: energy efficiency and sustainability by Spellman, Frank R.

Stave, K. A. (2003). A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada. Journal of Environmental Management, 67(4), 303-313.

Stephen, H., Ahmad, S. and Piechota, T.C., 2010. Land surface brightness temperature modeling using solar insolation. *IEEE Transactions on Geoscience and Remote Sensing*, *48*(1), pp.491-498.

Stillwell, A.S., Hoppock, D.C. and Webber, M.E., 2010. Energy recovery from wastewater treatment plants in the United States: a case study of the energy-water nexus. *Sustainability*, *2*(4), pp.945-962.

Stover, E.L., Haas, C.N., Rakness, K.L. and Scheible, O.K., 1986. Design manual: municipal wastewater disinfection. *Cincinnati Ohio, US Environmental Protection Agency*.

Sweeney, J.F., Pate, M.B. and Choi, W., 2016. Life cycle production and costs of a residential solar hot water and grid-connected photovoltaic system in humid subtropical Texas. Journal of Renewable and Sustainable Energy,8(5), p.053702.

Tamaddun, K., Kalra, A. and Ahmad, S., 2018. Potential of rooftop rainwater harvesting to meet outdoor water demand in arid regions. *Journal of Arid Land*, *10*(1), pp.68-83.

Tamaddun K, Kalra A, Ahmad S. (2016) Wavelet analysis of western U.S. streamflow with ENSO and PDO, Journal of Water and Climate Change, DOI: 10.2166/wcc.2016.162

Tamaddun, K.A., Kalra, A., Bernardez, M. and Ahmad, S., 2017. Multi-Scale Correlation between the western US Snow Water equivalent and ENSO/PDO using wavelet analyses. Water Resources Management, 31(9), pp.2745-2759.

Tan, C. and Zhi, Q., 2016. The energy-water nexus: a literature review of the dependence of energy on water. Energy Procedia, 88, pp.277-284.

Tang, O. and Rehme, J., 2017. An investigation of renewable certificates policy in Swedish electricity industry using an integrated system dynamics model. *International Journal of Production Economics*.

Thakali, Ranjeet, Ajay Kalra, and Sajjad Ahmad. Understanding the effects of climate change on urban stormwater infrastructures in the Las Vegas Valley. *Hydrology*3, no. 4 (2016): 34.

Tian, Y. and Zhao, C.Y., 2013. A review of solar collectors and thermal energy storage in solar thermal applications. Applied Energy, 104, pp.538-553.

Tidwell, V.C., Moreland, B.D., Zemlick, K.M., Roberts, B.L., Passell, H.D., Jensen, D., Forsgren, C., Sehlke, G., Cook, M.A., King, C.W. and Larsen, S., 2014a. Mapping water availability, projected use and cost in the western United States. Environmental Research Letters, 9(6), p. 064009.

Tidwell, V.C., Macknick, J., Zemlick, K., Sanchez, J. and Woldeyesus, T., 2014b. Transitioning to zero freshwater withdrawal in the US for thermoelectric generation. Applied Energy, 131, pp. 508-516.

Thomson, M. and Infield, D., 2003. A photovoltaic-powered seawater reverse-osmosis system without batteries. Desalination, 153(1), pp.1-8.

Timilsina, G. and Kurdgelashvili, L., 2017. 25. The evolution of solar energy technologies and supporting policies. *Handbook on Geographies of Technology*, p.362.

Timilsina, G.R., Kurdgelashvili, L. and Narbel, P.A., 2012. Solar energy: Markets, economics and policies. Renewable and Sustainable Energy Reviews, 16(1), pp.449-465.

Tjong, S.C., 2013. Nanocrystalline materials: their synthesis-structure-property relationships and applications. Newnes.

Tozzi, P. and Jo, J.H., 2017. A comparative analysis of renewable energy simulation tools: Performance simulation model vs. system optimization. *Renewable and Sustainable Energy Reviews*, *80*, pp.390-398.

Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R. and Sheffield, J., 2014. Global warming and changes in drought.Nature Climate Change, 4(1), pp. 17-22.

Tsoutsos, T., Frantzeskaki, N. and Gekas, V., 2005. Environmental impacts from the solar energy technologies. Energy Policy, 33(3), pp.289-296.

Turney, D. and Fthenakis, V., 2011. Environmental impacts from the installation and operation of large-scale solar power plants. Renewable and Sustainable Energy Reviews, 15(6), pp. 3261-3270.

UNO 2015. United Nations Organization (UNO). http://www.un.org/waterforlifedecade/water_and_sustainable_development.shtml (accessed 10 October 2016).

UNO, 2014a. United Nations Organization (UNO). The United Nations World Water Development Report 2014: Water and Energy. *United Nations, Paris*.

UNO, 2014b. United Nations Organization (UNO). Partnerships for improving water and energy access, efficiency and sustainability. Prepared by UN-Water Decade Programme on Advocacy and Communication (UNW-DPAC) with United Nations University (UNU) and United Nations Industrial Development Organization (UNIDO) In 2014 UN-Water Annual International Zaragoza Conference, 13-16 January 2014

U.S. Census Bureau, (2017). https://www.census.gov/population/international/data/worldpop/table_population.php (accessed 1 October 2017)

U.S. Census Bureau, 2016. https://www.census.gov/popest/data/counties/asrh/2015/PEPSR6H.html (accessed 20 July 2016).

U.S. Census Bureau, 2015 https://www.census.gov/geo/reference/boundary-changes.html (accessed 27 September 2016).

US Census Bureau, 2012. http://www.census.gov/popest/data/historical/index.html (accessed 15 September 2016).

U.S. Census Bureau, 2010. https://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml (accessed 27 September 2016).

USEIA, 2016a. U.S. Energy Information Administration (USEIA). http://www.eia.gov/todayinenergy/detail.cfm?id=26912 (accessed 20 September 2016).

USEIA, 2016b. U.S. Energy Information Administration (USEIA). https://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3 (accessed 24 August 2016).

USEIA, 2016c. U.S. Energy Information Administration (USEIA). http://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3 (accessed 24 May 2016).

USEIA, 2016d. U.S. Energy Information Administration (USEIA). http://www.eia.gov/state/seds/ (accessed 29 July 2016).

USEIA, 2017a. U.S. Energy Information Administration (USEIA). https://www.eia.gov/electricity/monthly/current_month/epm.pdf (Accessed 5 November 2017)

USEIA, 2017b. U.S. Energy Information Administration (USEIA). https://www.eia.gov/todayinenergy/detail.php?id=26212 (24 October 2017).

USEIA, 2017c. U.S. Energy Information Administration (USEIA). International Energy Outlook 2017. *US Energy Information Administration, Washington, DC*. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=1-IEO2017&cases=Reference&sourcekey=0 (24 October 2017).

USEPA, 2017. U.S. Environmental Protection Agency (USEPA). https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator (accessed 1 September 2017

USEPA, 2016a. U.S. Environmental Protection Agency (USEPA). https://www3.epa.gov/region9/waterinfrastructure/ (accessed 15 September 2016)

USEPA, 2016b. U.S. Environmental Protection Agency (USEPA). https://www.epa.gov/sites/production/files/2016-08/documents/scienceinaction_small_systems_final-508.pdf (accessed 20 September 2017)

USEPA, 2016c. U.S. Environmental Protection Agency (USEPA). https://www.epa.gov/dwstandardsregulations (accessed 12 October 2016).

USEPA, 2013. U.S. Environmental Protection Agency (USEPA). https://www.epa.gov/sites/production/files/2015-04/documents/epa816f13004.pdf (accessed 19 September 2016)

USEPA, 1987. Design Manual: Dewatering Municipal Wastewater Sludges (EPA/625/1–87/014). *Cincinnati OH*, *45268*.

Vadasarukkai, Y.S. and Gagnon, G.A., 2017. Influence of the Mixing Energy Consumption Affecting Coagulation and Floc Aggregation. *Environmental Science & Technology*, *51*(6), pp.3480-3489.

Valero, D., Ortiz, J.M., Expósito, E., Montiel, V. and Aldaz, A., 2010. Electrochemical wastewater treatment directly powered by photovoltaic panels: electrooxidation of a dye-containing wastewater. *Environmental science & technology*, *44*(13), pp.5182-5187.

van Vuuren, D.P., Stehfest, E., Gernaat, D.E., Doelman, J.C., Van den Berg, M., Harmsen, M., de Boer, H.S., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y. and Girod, B., 2017. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*, *42*, pp.237-250.

Venkatesan, A.K., Ahmad, S., Johnson, W. and Batista, J.R., 2011a. Salinity reduction and energy conservation in direct and indirect potable water reuse. *Desalination*, *272*(1), pp.120-127

Venkatesan, A.K., Ahmad, S., Johnson, W. and Batista, J.R., 2011b. Systems dynamic model to forecast salinity load to the Colorado River due to urbanization within the Las Vegas Valley. *Science of the Total Environment*, *409*(13), pp.2616-2625.

Von Medeazza, G.M., 2004. Water desalination as a long-term sustainable solution to alleviate global freshwater scarcity? A North-South approach.Desalination, 169(3), pp.287-301.

Vörösmarty, C.J., Green, P., Salisbury, J. and Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth.science, 289(5477), pp.284-288.

Wadhawan, S.R. and Pearce, J.M., 2017. Power and energy potential of mass-scale photovoltaic noise barrier deployment: A case study for the US. *Renewable and Sustainable Energy Reviews*, *80*, pp.125-132.

Wagner MJ, Newman AM, Hamilton WT, Braun RJ. Optimized dispatch in a first-principles concentrating solar power production model. Applied Energy. 2017 Oct 1;203:959-71.

Waite, J.L., 2017. Land reuse in support of renewable energy development. *Land Use Policy*, *66*, pp.105-110.

Wakeel, M., Chen, B., Hayat, T., Alsaedi, A. and Ahmad, B., 2016. Energy consumption for water use cycles in different countries: A review. Applied Energy, 178, pp.868-885.

WEF (Water Environment Federation) 2009. Energy Conservation in Water and Wastewater Facilities, Manual of practice No. 32Virginia: WEF Press.

Weiss, J.L., Castro, C.L. and Overpeck, J.T., 2009. Distinguishing pronounced droughts in the southwestern United States: Seasonality and effects of warmer temperatures. Journal of Climate, 22(22), pp.5918-5932.

Wen, H., Zhong, L., Fu, X. and Spooner, S., 2014. Water energy nexus in the urban water source selection_a case study from Qingdao. *Beijing: Water Resources institute*.

White, G.C., 2010. *White's handbook of chlorination and alternative disinfectants*. Wiley.

Wholesalesolar, 2017a. https://www.wholesalesolar.com/cms/crown-2crv1200-agm-2-volt-battery-specs-2243747105.pdf (accessed 6 September 2017).

Wholesalesolar, 2017b. https://www.wholesalesolar.com/2935110/fronius/inverters/fronius-symo-lite-10.0-3-10kw-3-phase-480-inverter (accessed 28 August 2017).

Wholesalesolar, 2017c.https://www.wholesalesolar.com/9901382/surrette-rolls/batteries/surrette-rolls-s-1660-flooded-battery (accessed 28 August 2017).

Wholesalesolar, 2017d. https://www.wholesalesolar.com/9949468/fullriver/batteries/fullriver-dc1150-2-agm-sealed-2v-1150ah-battery (accessed 4 January 2017).

Wiser, R., Barbose, G. and Holt, E., 2011. Supporting solar power in renewables portfolio standards: Experience from the United States. Energy Policy, 39(7), pp.3894-3905.

Wiser, R., Barbose, G., Heeter, J., Mai, T., Bird, L., Bolinger, M., Carpenter, A., Heath, G., Keyser, D., Macknick, J. and Mills, A., 2016. A retrospective analysis of the benefits and impacts of US renewable portfolio standards.Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory.

Withagen, C., 1994. Pollution and exhaustibility of fossil fuels. Resource and Energy Economics, 16(3), pp.235-242

Wong, L., 2011. A review of transmission losses in planning studies. California Energy Commission.

WRCC, 2016. Western Regional Climate Center (WRCC). https://wrcc.dri.edu/Climsum.html (accessed 18 November 2016)

Wu, P., Ma, X., Ji, J. and Ma, Y., 2017. Review on Life Cycle Assessment of Greenhouse Gas Emission Profit of Solar Photovoltaic Systems. *Energy Procedia*, *105*, pp.1289-1294.

Wu, G., Li, L., Ahmad, S., Chen, X. and Pan, X., 2013. A dynamic model for vulnerability assessment of regional water resources in arid areas: a case study of Bayingolin, China. *Water resources management*, *27*(8), pp.3085-3101.

Xu, Z., Liu, J., Huang, Z., Yang, X., Wang, S., Fang, F., Chen, S. and Wang, Y., 2017. Experimental study of a stand-alone solar-wind-powered reverse osmosis seawater desalination system. *Desalination and Water Treatment*, *78*, pp.24-33.

Xue, X., Hawkins, T.R., Schoen, M.E., Garland, J. and Ashbolt, N.J., 2016. Comparing the life cycle energy consumption, global warming and eutrophication potentials of several water and waste service options. *Water*, *8*(4), p.154.

Yang, C., Yeh, S., Zakerinia, S., Ramea, K. and McCollum, D., 2015. Achieving California's 80% greenhouse gas reduction target in 2050: Technology, policy and scenario analysis using CA-TIMES energy economic systems model. Energy Policy, 77, pp. 118-130.

Yaqoot, M., Diwan, P. and Kandpal, T.C., 2016. Review of barriers to the dissemination of decentralized renewable energy systems. *Renewable and Sustainable Energy Reviews*, *58*, pp.477-490.

Yuan, J., Xu, Y., Zhang, X., Hu, Z. and Xu, M., 2014. China's 2020 clean energy target: Consistency, pathways and policy implications. Energy Policy, 65, pp. 692-700.

Yushchenko, A., de Bono, A., Chatenoux, B., Patel, M.K. and Ray, N., 2017. GIS-based assessment of photovoltaic (PV) and concentrated solar power (CSP) generation potential in West Africa. *Renewable and Sustainable Energy Reviews*.

Zakkour, P.D., Gaterell, M.R., Griffin, P., Gochin, R.J. and Lester, J.N., 2002. Developing a sustainable energy strategy for a water utility. Part II: a review of potential technologies and approaches. Journal of environmental Management, 66(2), pp.115-125.

Zhang, H.L., Baeyens, J., Degrève, J. and Cacères, G., 2013. Concentrated solar power plants: Review and design methodology. Renewable and Sustainable Energy Reviews, 22, pp.466-481.

Zhang, H., Benoit, H., Perez-Lopèz, I., Flamant, G., Tan, T. and Baeyens, J., 2017. High-efficiency solar power towers using particle suspensions as heat carrier in the receiver and in the thermal energy storage. Renewable Energy, 111, pp.438-446.

Zhang, L.Z. and Li, G.P., 2017. Energy and economic analysis of a hollow fiber membrane-based desalination system driven by solar energy. *Desalination*, *404*, pp.200-214.

Zhang, S., Zhang, J., Wang, W., Li, F. and Cheng, X., 2013. Removal of phosphate from landscape water using an electrocoagulation process powered directly by photovoltaic solar modules. *Solar Energy Materials and Solar Cells*, *117*, pp.73-80.

Zhang, F., Ahmad, S., Zhang, H., Zhao, X., Feng, X. and Li, L., 2016. Simulating low and high streamflow driven by snowmelt in an insufficiently gauged alpine basin. *Stochastic environmental research and risk assessment*, *30*(1), pp.59-75.

Zhang, X. and Vesselinov, V.V., 2016. Energy-water nexus: Balancing the tradeoffs between two-level decision makers. *Applied Energy*, *183*, pp.77-87.

Zhang, Y., Sivakumar, M., Yang, S., Enever, K. and Ramezanianpour, M., 2018. Application of solar energy in water treatment processes: A review. Desalination, 428, pp.116-145.

Zoundi, Z., 2017. CO2 emissions, renewable energy and the Environmental Kuznets Curve, a panel cointegration approach. *Renewable and Sustainable Energy Reviews*, *72*, pp.1067-1075.

CURRICULUM VITAE

Syeda Saria Bukhary

University of Nevada Las Vegas
Department of Civil and Environmental Engineering and Construction
Email address: bukhary2@unlv.nevada.edu, bukhary477@yahoo.com

Education:

Master of Science, 2012, Civil Engineering, University of Nevada, Reno.

Master of Engineering, 2006, Civil Engineering, NED University of Engineering & Technology, Pakistan

Bachelor of Engineering, 2003, Civil Engineering, NED University of Engineering & Technology, Pakistan

Publications:

Bukhary, S., Ahmad, S. and Batista, J., 2018. Analyzing land and water requirements for solar deployment in the Southwestern United States. *Renewable and Sustainable Energy Reviews*, 82(3), pp. 3288-3305.

Bukhary, S., Batista, J. and Ahmad, S. Techno-economic assessment of using solar photovoltaic for a small water treatment plant. (Under review)

Bukhary, S., Batista, J. and Ahmad, S. Incorporating sustainability to offset the energy consumption of an existing drinking water treatment facility. (Under review)

Bukhary, S., Batista, J. and Ahmad, S. Energy-water nexus approach for large-scale water treatment. (Under Review)

Bukhary, S., Batista, J. and Ahmad, S., 2018. Sustainable Desalination of Brackish Groundwater for the Las Vegas Valley. In *World Environmental and Water Resources Congress 2018* (Accepted)

Bukhary, S., Batista, J. and Ahmad, S., 2017. Evaluating the Feasibility of Photovoltaic-Based Plant for Potable Water Treatment. In *World Environmental and Water Resources Congress 2017* (pp. 256-263).

Bukhary, S., Weidhaas, J., Ansari, K., Mahar, R.B., Pomeroy, C., VanDerslice, J.A., Burian, S. and Ahmad, S., 2017. Using Distributed Solar for Treatment of Drinking Water in

Developing Countries. In *World Environmental and Water Resources Congress 2017* (pp. 264-276).

Bukhary, S., Chen, C., and Ahmad, S., 2016. Analysis of Water Availability and Use for Solar Power Production in Nevada. In World Environmental and Water Resources Congress 2016: pp. 164-173.

Bukhary, S., Kalra, A. and Ahmad, **S.,** 2015. Insights into Reconstructing Sacramento River Flow using Tree Rings and Pacific Ocean Climate Variability. In *World Environmental and Water Resources Congress 2015* (pp. 1040-1049).

Bukhary, S., Chen, C., Kalra, A. and Ahmad, S., 2014. Improving Streamflow Reconstructions Using Oceanic-Atmospheric Climate Variability. In *World Environmental and Water Resources Congress 2014* (pp. 846-855).