

EFFECTS OF THE CHANGING CLIMATE ON HYDROPOWER PRODUCTION IN THE SACRAMENTO RIVER
WATERSHED AND CALIFORNIA'S ELECTRICITY PRICES

By

Daniel Fučík

B.A., Charles University Prague, 2012

B.A., University of Regensburg, 2012

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Approved by:

Dr. Silvia Secchi

Dr. Leslie Duram

Dr. Jonathan Remo

Graduate School
Southern Illinois University Carbondale

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MAJOR PROFESSOR: Dr. Silvia Secchi

Historically, hydropower is the largest renewable energy source. However, as it is strongly climate dependent, the current climate change is altering the generating conditions. The watershed of the Sacramento River in California houses the greatest concentration of hydropower plants in all of the United States. As such, it generates about 10 percent of all instate-produced electricity. This study examines the changes of climatic conditions within the watershed, as well as its effects on hydropower generation in this region. Changes – decrease in this case – in electricity supply can lead to an increase of electricity prices. It was found that the watershed's significance in California's electricity mix indeed decreased, though climate change is only one reason for this development. The other reason, next to the factual decrease in hydropower generation due to altered climatic conditions, is the large and rapid increase in solar and wind energy generating facilities. Despite the size and electricity generating capacity within the watershed, the change in climate and to it related change in hydropower generation did not have a significant effect on the state's electricity prices.

DEDICATION

I would like to dedicate this thesis to my parents, Vladimir and Iveta. I thank them for their ongoing support and encouraging my interests from young age. Thank you for your all your love and always pushing me forward.

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CHAPTER 1

INTRODUCTION

1.1 Objective of the study

The objective of this study is to determine to what extent the changing climate is affecting the production of electricity from hydropower, prices of electricity and possible outlooks for the industry. Production of electric power is a very systematic and complex process. Over the past few decades it has become clear that conventional methods of electricity production, which are based on nonrenewable fossil fuels such as coal or natural gas, will have to be replaced by sustainable, renewable sources of energy. This is why most developed countries are adopting policies which prepare and provide a transition to generating sustainable, “green” energy. The United States, for instance, is planning on producing 25% of all electric power from renewable sources by 2025, while Germany is aiming for 100% of all energy being produced from renewable resources by 2050 (Ittershagen 2010; DOE 2010).

There are several different ways how to transition from fossil fuels to renewables. New efficient, sustainable ways of energy production are steadily being researched, developed and improved. These are biomass, concentrated solar power, hydropower, geothermal power and still very young wave power. Hydropower, however, is currently the largest producer of power from a renewable source in the US. In 2010, 6.2% of all electricity was generated by hydropower (Energy Information Administration 2014). This is an average value for all 50 states. In some states, particularly those in the western part of the USA, the energy demand is satisfied by substantially larger hydroelectricity production. In California, 19% of electricity was produced from hydropower plants by 2006 (Smutny-Jones 2013). 60% of this hydroelectric power is also consumed in the state of California (Energy Almanac 2014).

1.2 Problem statement

Due to the changing climate, it is expected that the security of hydropower production in some regions will be affected. This applies especially to California, where at the beginning of the study period 19% of the state's electricity was generated from hydropower. One of the most important sources of water for hydropower production is precipitation retained in large reservoirs. The second most significant source of water is the snowmelt runoff from the Sierra Nevada that occurs in spring and summer months (Barnett, Adam, Lettenmaier 2005). Both are strongly dependent on climatic conditions. It is estimated that by 2050 the temperature will rise by 1-2°C, which will cause a dramatic reduction of the snowcap, which now serves as water storage. Even though studies have not proven a statistically significant shift in snow precipitation, the change in temperature will affect the rate at which the overall snowpack will melt, as well as the periods during which the snowmelt will happen. This will not only have impact on the peak flow in California's rivers, but might impact the electricity prices (Kiparsky et al. 2014).

This undergoing change might be more critical to hydropower production in some regions of the state than in others. The Sacramento River watershed that stretches from the northeastern corner of the state to Sacramento, and is enclosed by the Sierra Nevada in the east and the Northern Coast Ranges in the west, includes some of the largest rivers in California, such as the Pit, Mc Cloud, Feather, American, Yuba and Sacramento River (Sacramento River Watershed Program 2010). The geographic and hydrologic conditions in this region were the reasons for the construction of numerous hydropower projects. Today, the Sacramento River watershed has the largest concentration of hydropower plants in the United States. It consistently supplies about half of California's hydropower. As such, this region is crucial to the state's electricity market and any changes to its water supply might have vast going consequences the composition of the electricity mix in the state.

1.3 Research questions:

As this study is describing the effects of climate change on hydropower production, the following research questions will be addressed:

Does the changing climate have a significant impact on hydropower production in the Sacramento River watershed? As mentioned in the introduction, there are two main sources of water – precipitation in form of rain, and snowmelt runoff. Both are retained in large scale dams and both are strongly seasonal and related to the climate. With changing climate, the patterns of both rainfall and snowmelt can change or be shifted substantially. Without sufficient water supply, the electricity production from hydropower would decrease. This might be particularly problematic, as releasing water into turbines at certain points of the day generates electricity that covers peak demands. Thus, the overall production might decrease, and the critical role in peak demand periods might be weakened.

Furthermore, with changing climate the stream temperatures and adjacent habitats might change. Hydropower dams have also the quality of controlling and adjusting the stream's temperature through water release management. In other words, generating or not generating electricity at times in the future might decide about a habitat's further existence.

Do climate change and its related changes in hydroelectricity generation in the Sacramento River watershed impact electricity prices?

The electricity network is highly vulnerable to sudden and extreme weather conditions. Power outages or shortages due to such events are especially common in connection to renewable energy sources. Temperature and precipitation records suggest that severe rainfall or drought are more likely to happen today than 30 or 40 years ago (Davis and Clemmer 2014). The average cost of extreme weather events rose from \$25 billion annually in 1980's to approximately \$80 billion in the 2010's (Weiss and

Weidman 2013). But power outages are not the only consequence. A heat wave – or warmer climate in a region – will cause increased demand for electricity for cooling. At the same time warmer climate can change and shift the snowmelt runoff patterns and different precipitation patterns could impact water availability. That is water that in some regions – such as the research area – is crucial to electricity generation. All these aspects have the potential to significantly influence the prices of electricity in a region.

1.4 Significance

California, as a state with the largest economy in the U.S., has a steadily growing demand for electricity. Currently, hydropower is California's largest renewable energy resource. However, the future of hydropower in some regions is uncertain. In particular, the southern portion of the state has been facing disturbingly low water levels in lakes and reservoirs. Though not as drastic, even the precipitation-rich north of the state has recorded a significant decline in water reserves (DWR 2016). At the same time, California is bound by the Renewable Portfolio Standard to increase its electricity production from renewable resources. Thus, it would not be politically – and often economically as well – viable to turn towards unsustainable energy sources such as coal or natural gas to meet decrease in hydropower electricity production.

There is very little literature combining climate change and its effects on electricity prices and hydropower in particular. This thesis analyzes how crucial hydropower is to the research area and whether or not the changing climate actually impacts electricity production and prices, and if so how severely. The findings of this study will provide a basis for further research to help determine energy allocation and investment in California, in particular to assess the trade-offs between maintaining hydropower facilities or finding alternative renewable sources for electricity generation.

CHAPTER 2

LITERATURE REVIEW

The ability to produce hydropower depends on several variables: how climate change affects the water cycle; how the changes in water availability impact the hydroelectric industry, and the costs and benefits of offsetting such impacts. Thus, this chapter is divided into three parts. In the first section the impacts of the changing climate on water availability in California will be described. The focus of this section is an analysis of the changing climate signs. This section will focus on (1) changed temperature, (2) development of precipitation and shift in precipitation patterns and (3) changes in available surface water in the state of California. The second section will describe how hydropower generation is impacted by the altered hydrologic conditions. Changes in hydropower production on the Sacramento river will be addressed as well as the role of hydropower from this region to California, production capacity, the possible impacts of the changed climate on the hydropower production and the overall impact on California's energy market.

2.1 Changes in Precipitation and Temperatures

Changing climate is a phenomenon that has been analyzed by many researchers over the past few decades. Today there are no doubts among scientists the climate is changing and temperatures are rising. Studies concerned with climate change generally agree that there has been a significant change in temperature (worldwide over one degree Celsius over the last hundred years, locally possibly even more), increased frequency in extreme weather events and shift in precipitation patterns (Luers et al. 2006). This applies both to global and regional scales. A study by Duliere, Zhang and Salathe shows that the mean temperature of Earth's surface rises due to global warming, which has effects on the local climates. The study also suggests that this also leads to more frequent warm temperature events and

more frequent extreme temperature events (Duliere, Zhang and Salathe 2009). It is expected that, despite the current trends in CO₂ emission reduction and climate change mitigation, the temperature will keep rising. Researchers expect that by 2050 global temperatures will rise by 1 – 2° Celsius (Barnett, Adam, Lettenmaier. 2005).

It is important to mention that researchers agree that these climate-change trends are largely human induced as it was shown by Barnett et al. (2008) using different climatic models, such as the Parallel Climatic Model (PCM) or the Model for Interdisciplinary Research on Climate (MIROC). Rising temperatures have more far-reaching impacts than simply “milder winters” or “more frequent storms”. Climate change has effects on precipitation and overall water availability on as well. Increased temperature causes increased evaporation, which causes soils to dry out. Trenberth has proposed that the water holding capacity of air increases, by 7% for each 1° Celsius. Such increase of vapor in the atmosphere would cause extratropical rain or snow storms, cyclones and generally increased precipitation during singular rainfall events, because the higher atmospheric vapor would supply the necessary moisture. Beyond this, drier soil combined with increased precipitation amounts increases the risk of flooding since the soil has reduced capacity to absorb water.

As of now, it is safe to say, that both precipitation patterns and precipitation amounts have changed. And this trend is likely to continue (Kiparsky and Gleick 2003). However, this trend differs from place to place – while in the tropics and subtropics a decrease in precipitation has been noted, at higher altitudes, notably in North America, Eurasia and Argentina there has been increase in precipitation (Trenberth 2011). In the United States in particular, the precipitation has increased by 10% since 1910. Furthermore, the frequency of very heavy and extreme precipitation days has increased, as well as the average probability of rainfall on any given day (Kiparsky, Gleick. 2003).

In California itself the temperature has risen by 0.6° Celsius since the 1960's and it is estimated

that it will rise by another 2-4°C by the end of this century. As far as precipitation in California is concerned, Karl, Melillo and Peterson in their study *Global Climate Change Impacts in the United States*, conducted under the U.S. Global Change Research Program, avoid stating whether the precipitation increased or decreased, but they generally state that precipitation trends “changed” in terms of variability in rainfall amounts as well as precipitation patterns. The changing climatic and precipitation conditions will be especially challenging for the state of California. More than a half of the state’s water originates from precipitation. Considering the already decreasing water levels, continuous drought and expected shifts in precipitation, it is to be expected that California’s water scarcity will become an even more serious issue (Karl, Melillo and Peterson. 2009). It is important to note that, in general, even though overall precipitation over the United States has increased during the past decades, there are disagreements about future developments (Pierce et al. 2013).

Given that in California, the majority of the rivers originate, or go through, the eastern mountain range of Sierra Nevada, most of the rivers depend of the snowpack and snowmelt. Rising temperatures are causing a shift in the snowmelt runoff patterns. Due to the increased temperature peaks snowmelt will occur 1–2 months earlier. This shift can be very problematic in terms of water infrastructure, since higher temperatures will cause greater melting rate which the reservoirs might not be able to retain.

Additionally, substantial reduction of the snowpack over the next decades is expected (Barnett, Adam, Lettenmeier. 2005; Kiparsky et al. 2014).

2.2 Hydropower and Electricity Production

Hydropower energy is one of the cleanest, most efficient and cheapest ways to generate electricity. According to the World Bank, turbines used in modern hydropower facilities can transform mechanical energy into electrical energy with 85-95% efficiency. At the same time the efficiency of gas

turbines lies somewhere around 60% (Joyce, 1997). The efficiency of other renewable sources is less than half that of hydropower. Photovoltaic panels have an efficiency rate of 45% (Sechilariu, Locment, Wang 2015). Wind turbines usually generate around 30% of their theoretical maximum output, as climatic conditions are rarely optimal (Global Wind Energy Council 2014).

Currently, hydropower produces between 10-30% of all energy produced in all of California, depending on hydrologic conditions. The hydropower sector in California is a mature industry – the era of building new dams in California ended about 35 years ago. Today, most of the streams that can facilitate a large scale dam are already built up. Furthermore, funds for large infrastructure projects are not available with such “ease” as it was the case in the 1960’s and 1970’s (Gielen, 2012), and this is a crucial issue for hydropower since 80% of the overall costs over the life time of a dam are capital costs. There are also environmental barriers to new dam construction, since the 1973 Endangered Species Act made it legally more difficult to interfere with streams in ways that are potentially harmful to its habitats (Endangered Species Act 1973).

California’s hydropower facilities can be divided into high elevation and low elevation power plants. The high elevation power plants – at or above elevations of 1000 feet – are usually ones with smaller retention capacities (Madani, Lund. 2009). The shifts in peak precipitation and runoff would affect especially the facilities with smaller storage volume. Lower elevation facilities have usually much larger storage capacities. Three of California’s major dams with hydroenergy producing facilities are located in the Sacramento River Watershed: the Shasta Dam, the Oroville Dam and the Folsom Dam. These three dams alone have a production capacity of 1557 MW, which is more than 10% of the cumulative capacity of all hydropower plants in California (California Energy Commission 2014). This illustrates how the Sacramento River Watershed is crucial for hydropower production in California. Most of the studies that will be used in this literature review were prepared by different agencies for the California Energy Commission. One study prepared the Aspen Environmental Group thoroughly analyzes

California's hydropower infrastructure and stands out especially thanks to its differentiation between investor owned utilities, municipality-owned utilities and state-owned utilities (Jones, Smith, Korosec 2005).

The overall share of hydroelectricity in California's grid has been in slight decline over the past few years. Within the past three years, the portion of electricity from hydropower was pushed back by 7% (DOE/EIA 2013). According to a study by the California Climate Change Center, this decrease could go up to 40% by the end of the century (Medelin et al. 2005). However, the decrease could be due to either reductions in hydroelectricity generation, or to increased production from other electricity sources, such as solar or wind power. This reduction is happening within a general trend in energy consumption. This is due to the steadily growing economy and population of the state, and to more frequent engaging of air conditioning devices due to more frequent heat events and overall rising average temperatures (Ko and Radke 2014). A study by Guido and Sanstad suggests that with the rising temperature – that could reach up to 6° Celsius by the end of the century – annual energy demand would rise by up to 20% due to the increased use air conditioners and other cooling utilities (Franco, Sanstad. 2006). The authors look at the costs that would be connected with the reduced hydropower output in this case and find that if by 2020 energy demand rises by 3%, the average annual energy costs could increase by up to one billion dollars (Franco, Sanstad. 2006).

Since California is far ahead of every other U.S. state in climate change regulations, the pressures on electricity generation from both the demand and supply side raise an important question – is California's climate legislation putting the state to an economic disadvantage? The emphasis on increasing renewable energy in the overall energy mix causes increased investments into the renewable portfolio, which again might affect the electricity prices. Governor Brown agrees that being the leader comes with a cost, however, it not only provides numerous new opportunities, but it also initiates the development of more efficient technologies (Brown 2014). In 2007, the California Energy Commission

(CEC) predicted that electricity would grow at an annual rate of 1.8%, minus some 0.3% due to inflation-adjusted real dollars. However, this was long before the critical drought and water supply shortages (Marks 2007).

2.3 Evolution of electricity prices

Currently the Californian electricity system includes both regulated and deregulated markets. Among the most important factors that drive the prices of electricity are:

- cost of generating electricity
- cost of building and maintaining existing assets, and investing into the infrastructure
- demand and supply
- government policies.

As some 60% of California's electricity comes from natural gas powered power plants, the price of natural gas is the key driver of retail electricity prices (DOE/EIA 2013). Nationwide, electricity prices have increased significantly since the 1970's. According to the Energy Information Agency's (EIA) Energy Outlook for the year 2009, electricity prices increased by 85% over the past 25 years (EIA 2009). The price growth has been particularly sharp in the commercial and industrial sector, where it experienced two major jumps. First during the 1970's fuel crisis, and second during the 2001 electricity crisis. Prices during both these events went up by up to 30% within few months. It is projected that the prices will continue rising. The EIA Energy Outlook 2015 predicts an 18 percent increase in average electricity retail price between 2014 and 2040.

The three currently mostly used types of renewable energy resources – solar, wind, and hydro – power plants have very different capital costs and operating costs. When compared to conventional

power plants that are using fossil fuels, natural gas or nuclear fuel rods, the first obvious advantage of renewable energy resources is the free availability of their “fuels”. However, due to the relatively challenging and site sensitive construction issues, the capital costs for creating a hydropower system with storage are comparatively high, and with a wide range. Typically, the installed capital costs for large hydropower plants range from \$1,050/kW to 7,650/kW. The range for small hydropower projects is from \$1,300/kW to \$8,000/kW. On the other hand, once built, the refurbishment or upgrade costs are \$500/kW - \$1000/kW (Gielen 2012). Hydropower turbines also have the highest capacity factor – up to 90 percent. Because the installed costs vary widely, the operation and maintenance costs are usually presented in percent of the plants installed cost. The operation and maintenance costs for large hydropower plants average around 2 – 2.5 percent of the installed cost annually, while for small hydropower plants the costs average between 1 – 4 percent (Gielen 2012). Capital costs of wind farms usually range from \$2,000/kW to \$2,200/kW. However, the capacity factor is significantly lower than for hydropower plants, and averages between 30 – 45 percent. The maintenance costs for wind farms are typically between \$0.005 and \$0.015/kWh. The capacity factor on off-shore facilities can reach up to 50 percent, and both the capital and the operation costs are more than double of the on-shore facilities, however (Gielen 2012). Finally, the capital cost for a utility scale solar power plants ranges from \$3.6 to \$5/W. Solar panels, however, have the lowest efficiency of all mentioned technologies. The capacity factor for photovoltaic panels is typically between 10 and 20 percent. The operation and maintenance cost of solar power plants are estimated at 9 percent of the installed cost annually according to the EIA (DOI/EIA 2015).

The underinvestment in the grid infrastructure is particularly problematic. Between the 1970’s and 1990’s the demand for electricity rose by over 50%. However, in the same period the annual investment into new transmission capacity fell from \$5.5 billion a year to less than \$3 billion

(BloomEnergy 2010). The California Independent Service Operator (CA ISO) estimated that California will have to invest about \$5 billion to update its current electricity system and another \$2.5 billion will be needed in investments to accommodate the growing demand caused by growing population and economy (Mills, Wiser, Porter 2009). This number might grow even more, as the construction costs have increased from 25% to 100% since 2000 (Chupka and Basheda 2007).

When looking at hydroelectricity, there is historical evidence that changes in production from this source affected electricity prices state wide. According to Pope (2002), hydroelectric production between January 2000 and June 2001 decreased by 20% compared to prior years. This caused a significant shortage in supply and contributed strongly to the electricity crisis. The majority of the supply shortage was supplemented by natural gas fired power plants (Pope 2002). However, this caused natural gas prices to quadruple, and they never returned to pre-2001 levels. The CEC estimated that the natural gas prices will double between 2008 and 2018 (CEC 2009).

The other side of the electricity market that drives electricity prices after demand is the supply. The implementation of the California RPS, and the presence of newer, more efficient and affordable photovoltaic and wind power sources have been driving a rapid increase in electricity supply from those two sources. At the beginning of the research period, in 2001, solar and wind energy combined produced barely 4,000 GWh, but in 2014 these two sources produced about 25,000 GWh. For the first time in California's history, in February and March of 2014 wind generation alone surpassed hydro generation (EIA 2014). The ongoing drought is only worsening hydropower's position. According to Peter Gleick from the Pacific Institute California residents have experienced \$1.4 billion extra cost due to the shortfall in hydropower generation (Gleick 2015). Solar power capacity in the state rose from 2,000 GWh in 2012 in almost 11,000 GWh in 2014 (CEC 2014). According to Gleick, the increase in solar generation would have happened even without the drought, since the demand for renewable energy is continuously growing, but it would perhaps happen at a slower rate.

Thus, there are two major reasons for declining hydropower supply in the overall California electricity mix: an actual decrease in hydropower generation due to insufficient and inconsistent water supply, and an increased supply of electricity from other renewables such as wind and solar power that is driven by a continuously growing electricity demand. However, hydropower remains unbeaten – among renewable energy sources – when it comes to covering peak demand. Neither solar, nor wind energy can compete with hydropower’s ability to quickly and cheaply generate larger amounts of electricity at peak demand moments.

2.4 Policy drivers

The state of California can be referred to as America’s pioneer in green policies, climate warming science and renewable energy utilization. It has several “First in the U.S.” policies and initiatives of its kind, such as the creation of the Los Angeles Air Pollution Control District in 1947, the California Air Resource Board in 1967, and the Appliance Efficiency Standard in 1977. Many more of these “first” policies were added in the 2000’s. One of the first, most relevant bills actively addressing climate change was the 2000 Senate Bill SB 1771, through which the California Climate Action Registry (CCAR) was established (SB 1771 Senate Bill). The purpose of the CCAR was to provide a voluntary registry to help companies control greenhouse gas (GHG) emissions and to promote actions towards GHG emission reduction by private companies and organizations (CCAR 2015). This program was terminated in 2010. In 2002 California instituted the state’s first Renewable Portfolio Standard, which requires electricity companies to expand their renewable portfolio by at least 1% per year. The ultimate goal is 20% of the retail sales being generated from eligible renewable resources before December 31, 2017 (SB107 Senate Bill).

All this paved the way for the Assembly Bill 32 of 2006, also known as the Global Warming

Solutions Act of 2006. This bill establishes GHG emission targets for California. Specifically, these were to reduce emission levels to the levels of 2000 by 2010, to reduce emission levels to the levels of 1990 by 2020, and to reduce emissions to 80% below the 1990 levels by 2050 (EPA 2015).

CHAPTER 3

METHODOLOGY

3.1 Study Area

According to the Federal Energy Regulatory Commission (FERC), there are currently 1,623 hydropower generating facilities in the United States that are operated by the public sector, local or state governments and other non-governmental entities. These 1,623 hydropower plants represent 92% of America's hydroelectric facilities. The other 8%, or 133, of the hydropower plants in the United States are operated through the U.S. Bureau of Reclamation and through the U.S. Army Corps of Engineers. Out of these 1,756 facilities nearly 260 are located in the state of California. This study focuses on the watershed of the Sacramento River, as it is the major river in Northern California which has been heavily used for hydroelectricity production since the 1950's. Not only has the Sacramento River itself been used for energy production, the vast majority of its tributaries as well. Some of the largest and most significant dams and hydroelectric facilities in the U.S. were constructed within the watershed. These are the Folsom Dam, the Shasta Dam and the Oroville Dam. The Sacramento River watershed stretches out over 17 counties and is home to almost 260 hydroelectric facilities. The different sizes of its tributaries, the importance of the river to hydropower production and to California as a whole, the amount of hydropower plants located on the streams and the variability of yearly discharge rates and their seasonal irregularity make this watershed a perfect research site. Furthermore, the watershed is rather unique due to its diverse water sources. The Sacramento originates in the Klamath Mountains and runs through a mountainous landscape before it reaches the flat Sacramento Valley, which makes the river snowmelt fed. At the same time, the Sacramento receives more than two thirds of Northern California's precipitation. This ensures a somewhat secure supply of substantial amounts of water.

3.2 Data

Since this study considers inputs from three completely different scientific areas – climatic conditions, hydropower generation, and electricity markets – large amounts amount of data from various, area specific sources are needed. For completion of the first part of this thesis data on precipitation and temperature from within the Sacramento River Watershed had to be obtained. Despite the fact that the Sacramento flows for 445 miles before reaching the San Francisco bay, and despite the amount of its tributaries, the watershed is entirely within the borders of California. Therefore, most of the data was available through local and state agencies, such as the California Energy Commission (CEC) or the California Department of Water Resources (CalDWR), and major national water and energy agencies.

The time frame of analysis for this thesis is determined by the availability of all necessary data – climate, hydropower generation, and electricity pricing. Most weather and climate agencies provide recorded precipitation and temperature data on a daily basis. However, putting together daily data for a 14 year period would result in an enormous, unnecessarily detailed dataset. More importantly, however, neither the EIA, CEC, or DOE, nor the utility companies provide power generation or electricity prices on a day-to-day scale, and the data is available only on a monthly basis. Furthermore, monthly electricity generation and pricing data are only available from January 2001, and before then, only annual average electricity generation data are available. Thus, the January 2001 – December 2014 time frame of the thesis is based on availability of the data.

Even though California is not known for its high precipitation rates, rain is still the major source of water in the Sacramento (Fassnacht and Records 2015). Thus, the first step in the data collection process was to collect precipitation data from the watershed's region. Those were available in the databases of following agencies:

- National Oceanic and Atmospheric Administration

- Southern California Geographic Coordination Center (subdivision of the National Geographic Area Coordination Center)
- California Climate Data Archive
- Western Regional Climate Center - National Center for Atmospheric Research
- PRISM Climate Group.

Changes in precipitation over the research area were measured over the years 2001 to 2014, both as the annual rainwater amounts, as well as changes in precipitation patterns. As described in the literature review section of this paper, there are indicators that there has been a shift in peak precipitation and overall precipitation patterns.

Secondly, California's electricity data were obtained and analyzed. No power sector can be observed in isolation, due to the high substitutability of energy sources, so data for electricity generation were considered, as well as electricity consumption, imports, and exports. This information about California's electricity sources is crucial to determine what role hydropower plays at the state level, and specifically – as it is the goal of this paper – what role the Sacramento River watershed plays in the state's overall electricity mix. For a thorough analysis, we mapped out the hydroelectric facilities that lie within the watershed's boundaries, each power plant's capacity, what is the total electricity generating capacity and the real output of the Sacramento River watershed. For the completion of this task, datasets and shapefiles from the following sources were used:

- U.S. Energy Information Agency
- Department of Water Resources
- California Natural Resources Agency
- California Energy Commission
- U.S. Geological Survey

- Department of Energy.

Thirdly, electricity prices were tied to electricity production. This demonstrates how electricity prices evolved throughout the research period. Furthermore, linking electricity prices data with power generation shows how monthly electricity generation affects the prices within the state. Lastly, looking at the Sacramento River watershed's monthly net generation, it is possible to assess whether the significance of the watershed's hydropower facilities is such that it affects electricity prices at state level.

3.3 Objectives

In order to answer the research questions, several topics were addressed.

3.3.1 Location of powerhouses

First, the location of existing powerhouses within the Sacramento River watershed was determined. Having this information made it possible to focus on each power plant and its generation and variability in electricity generation. This shows not only the significance of the watershed for California's electricity mix as a whole, but also its link to the variability in climate as discussed later in the thesis.

3.3.2 Distribution of hydroelectricity production

Second, compiling monthly precipitation and temperature data for a period of 14 years provided the basis to empirically assess whether or not there has been a shift in those two climatic conditions, and if so, how significant those have been. As stated in the paragraph above, these data were then tied to

the same-time hydroelectricity production in the research area in order to determine whether or not there is a statistically significant correlation between electricity production and the climate data.

3.3.3 Changes in temperature and precipitation patterns

Third, the evolution of electricity prices in California was analyzed. After obtaining electricity prices for the research period for different sectors, those had been tied to electricity production in the Sacramento River watershed. This allows us to see whether this region is in a position to affect electricity prices for the entire state. This step required incorporating the evolution of electricity demand and supply, which can also drive the prices of electricity. Finally, different environmental policy drivers were taken into account, as different policy strategies can greatly affect electricity prices.

CHAPTER 4

RESULTS

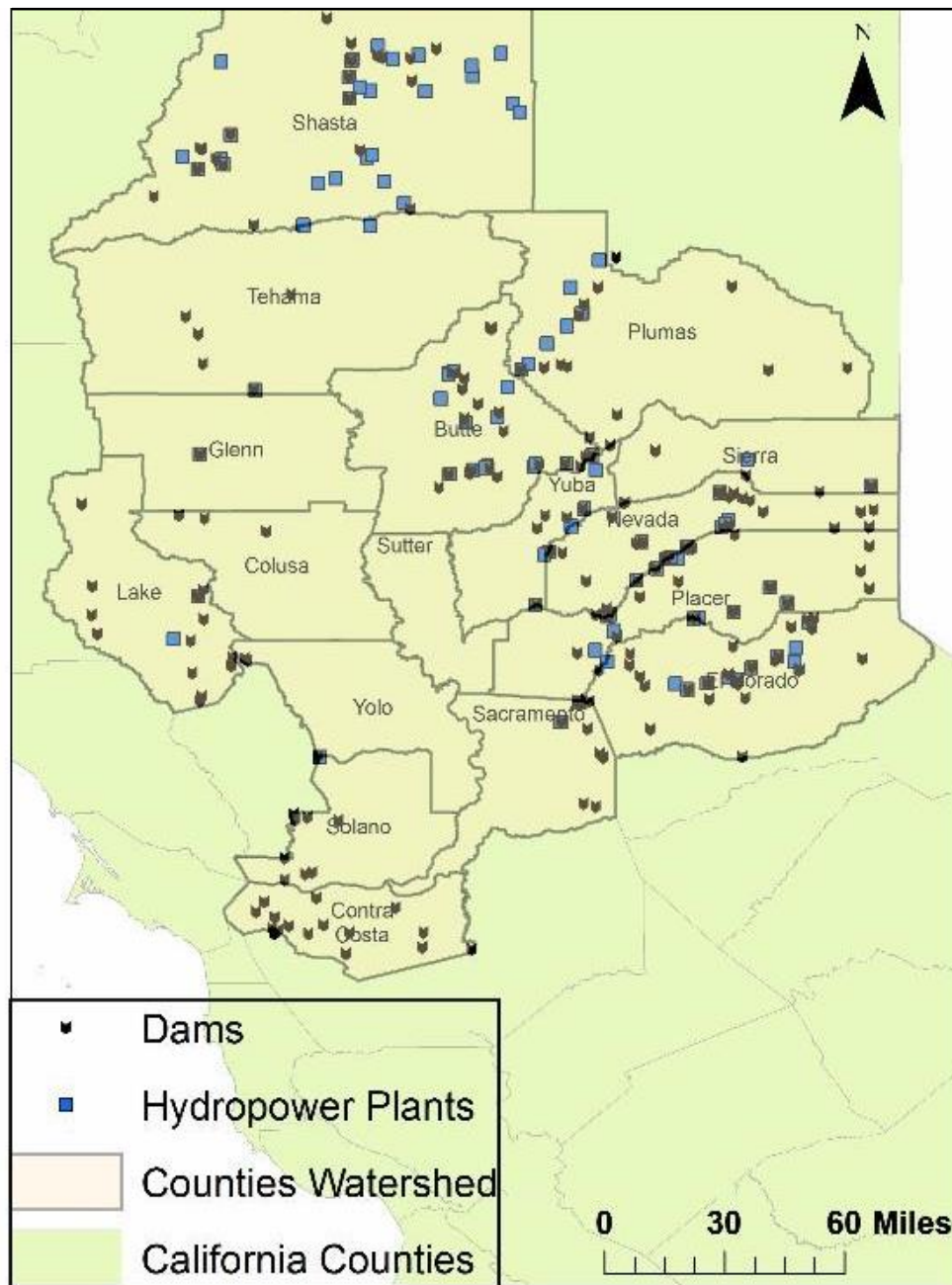
4.1 Distribution of electricity generation within the watershed

The state of California houses over 260 hydropower plants, which are housing over 500 electricity generating turbines. Around 100 of those are located in the Sacramento River watershed. The watershed area spreads out over 17 counties (Butte, Colusa, Contra Costa, El Dorado, Glenn, Lake, Nevada, Placer, Plumas, Sacramento, Shasta, Sierra, Solano, Sutter, Tehama, Yolo, Yuba) – as depicted in Figure 1 – covering a total area of 25,116 square miles. The number of hydropower plans in this region is not constant, since in some years some powerhouses had to be shut down due to low flows or due to maintenance or construction work. For instance in the year 2004 there were only 95 hydropower plans in operation, while in 2010 there were 99 power plants generating and supplying electricity into the network.

The powerhouses are not equally dispersed either. Even though there were 197 dams within the research area in 2014, only 98 of them also included a turbine for electricity production. The two southernmost counties (Contra Costa, Solano), although still contributing into the watershed, do have 22 dams on their streams, but no electricity generating facility. That is also the case for Sutter County, which has neither any hydroelectricity generating facility, nor any dams. This might seem rather surprising, as Sutter County lies very central in the watershed, where also many streams merge, and where the borders of the county are made up of the Sacramento River in the west and the Feather River in the east. The reason is simple – minimal to no slope, large amounts of water, and high quality soil make the county the agricultural heart of the state. 88% of the county's area is farmland or grazing land.

The absolute majority of the powerhouses are located on the western slopes of the Sierra

Nevada, and in the Klamath Mountains in the north of the research area. Only the plants Monticello (EIA ID - 7646), Clear Lake (50128), Indian Valley (50129), Stony Gorge (7151), and Black Butte (7229) are located west of the Sacramento Valley. At the same time, all these plants are classified as small hydro, with generating capacity under 30 MW. In fact, the greatest concentration of hydroelectric facilities within the watershed are located on the South Fork American River, a major tributary to the American River in Eldorado County, the Bear River, which constitutes the border between Placer and Nevada counties. Further north, the major electricity producing streams are the South Fork Feather River and North Fork Feather River, and several smaller streams in the northernmost Shasta County, including the Sacramento River and Yuba River. In other words, despite the relatively large size of the watershed the electricity production is fairly concentrated into the seven counties in the Sierra Nevada and in the Klamath mountains.



HYDROPOWER PLANTS AND DAMS LOCATIONS

Figure 1: Locations of the 99 hydropower plants and 197 dams spread over the 17 counties of the Sacramento River Watershed. Sources: US Census Bureau 2014 (California Counties, Counties Watershed); EPA 2014 (Dams); CEC 2014 (Hydropower Plants).

Between the years 2001 and 2014 California was producing 31,500 GWh from hydropower on average. However, the actual generation varied considerably from year to year. The yearly production ranged from 16,477 GWh in 2014 to 48,559 GWh in 2006. The hydropower generating facilities within the Sacramento River watershed quite steadily supplied about a half this number, as the Figure 2 indicates. Average annual production from this region is 16,430 GWh. The range of values from within the watershed is significantly smaller than for the whole state. The year 2014, with 9,429 GWh, was the year with the lowest electricity production level. The top electricity amount had been generated in 2006, when the watershed produced 25,493 GWh.

Because hydropower generation is strongly affected by seasonal patterns, such as rain or snowmelt runoff, the variability between months is even more substantial. Over the course of 14 years there are 168 monthly electricity generation values. The lowest monthly value from within the watershed is from February 2014 when 348,104 MW was generated. On the other hand the most productive month in the 14 year period was May 2006 with 3,052,380 MW.

As for the distribution of small and large hydroelectric facilities, about one third of the total number of power plants is classified as large hydro, with the rest is small hydro with generating capacity under 30 MW. However, as noted above, the exact numbers vary year by year as well, as some powerhouses need to be shut down for different periods of time. The number of large hydroelectric facilities is more stable than that of small hydroelectric facilities. For instance, in 2001, there were 36 large hydro facilities and 63 small hydro facilities in operation. The higher variability in operating small hydro facilities is due to two main reasons – some of the power plants are located on very small streams, which are affected more severely by dry periods. If the water levels drop below the minimal instream flow requirement, or if a stream dries out, the turbine needs to shut off. This usually does not happen for excessively long periods, however, if the production level drops below a minimum level, the EIA marks the facility's output at "NM = Not Meaningful" (EIA 2015). The other reason is maintenance or

construction work on the facilities. Large hydroelectric facilities have several turbines, or they consist of several units. If a turbine in such power plant needs to be turned off, there are still other units in operation. The output capacity will temporarily decrease, but the plant as a whole still generates electricity.

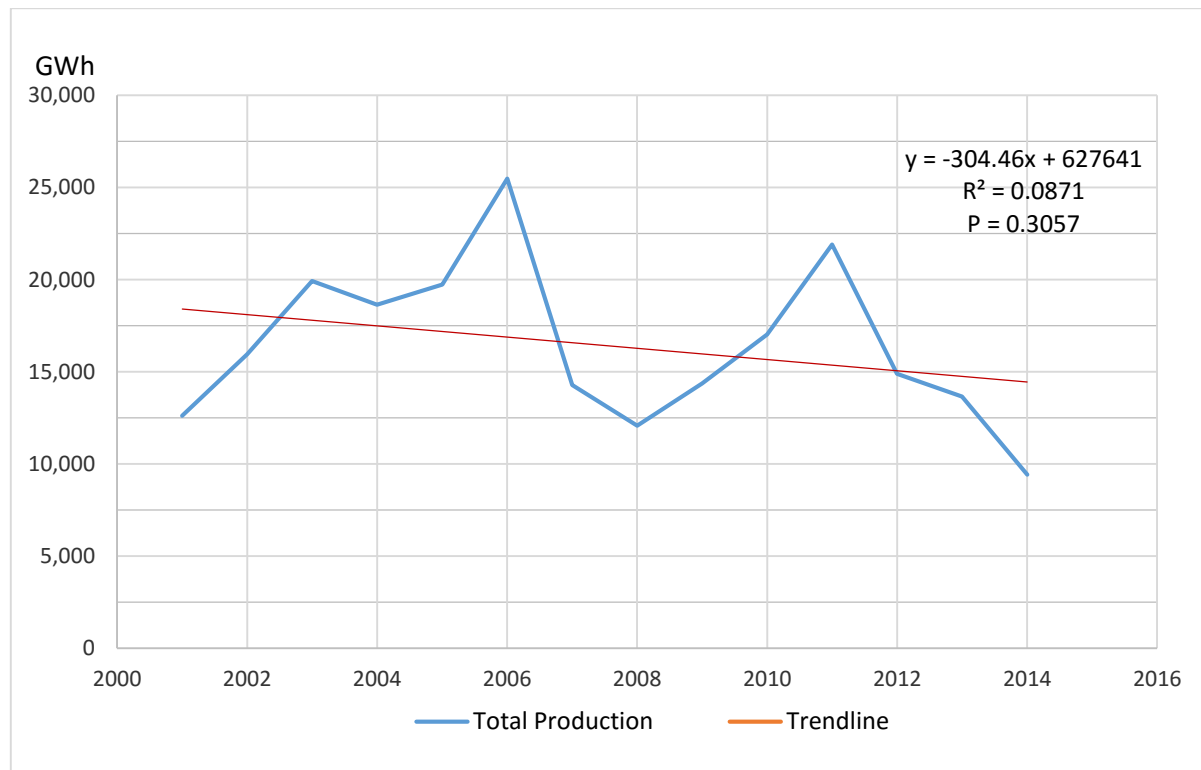
Of the 36 large hydroelectric facilities, 23 are classified as high elevation structures, located at or above 1,000 feet (305 meters). About 30 percent of California's water storage capacities lie at higher elevations, but at the same time high elevation power stations generate 74 percent of California's hydroelectricity (Guegan, Madani, Uvo 2012). Within the watershed, 68 of the 99 existing hydropower plants are located at high elevation. Madani and Lund (2009) have identified 156 hydropower plants above 1000 feet. Thus, nearly one half of California's high elevation hydroelectric facilities is located within the research watershed.

4.2 Effects of changing climate on the watershed's electricity production

One drawback of hydropower is its dependency on sufficient water supply, which has to find its way into the reservoir or the turbine from its natural environment – with the exception of pumped storage facilities. Changing climate affects seasonal precipitation patterns, and actual precipitation amounts, while rising temperature has an effect on snowmelt runoff patterns as well. The impact of climate on the Sacramento River watershed's ability to produce electricity over the past 14 years is linked to the behavior of these three variables.

The two main sources of water are rainfall and snowmelt runoff, with the latter supplying mainly high elevation hydropower stations (Guegan, Madani, Uvo, 2012). Over the research period, there has been a decline in overall electricity production, especially since 2006. While at the beginning of the 14 year period the watershed was producing close to 13,000 GWh per year, at the end in 2014 it was supplying less than 9,500 GWh per year, after hitting peak production of 25,493 GWh in 2006. After

reviewing the trend on Figure 2 below, it is clear that the average annual production dropped by some 3,000 GWh per year.



HYDROELECTRICITY FROM SACRAMENTO RIVER WATERSHED

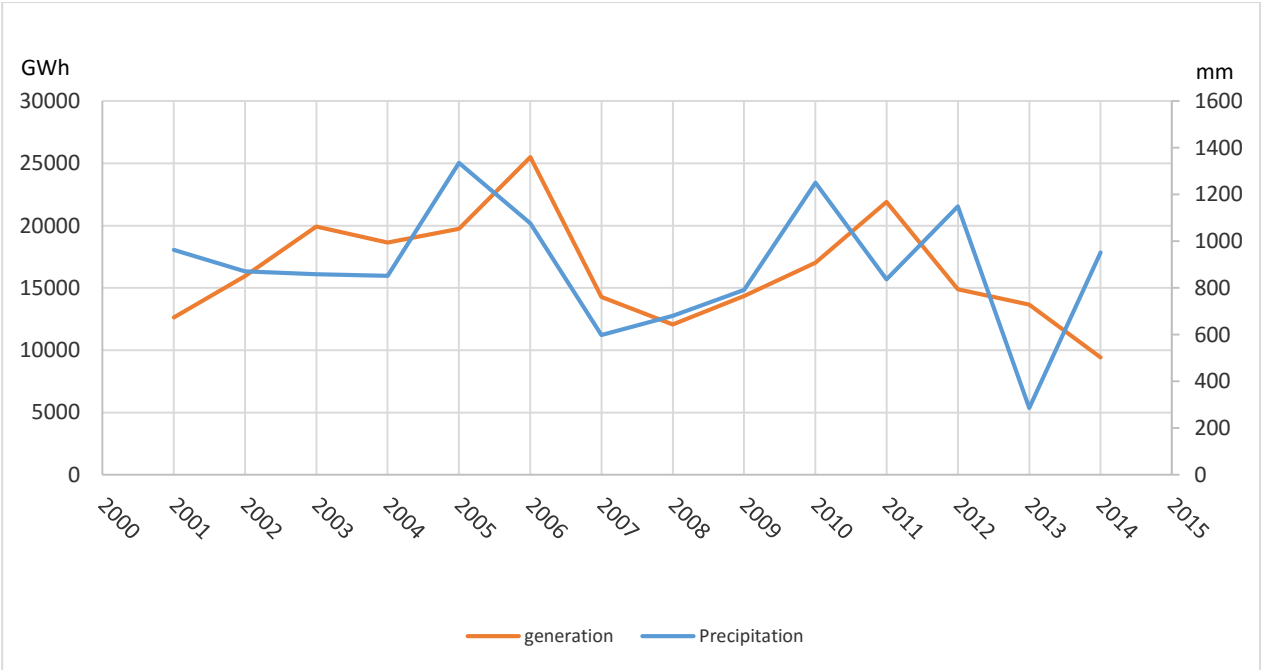
Figure 2: Energy generated from 95-99 operational hydropower plants (number of operational sites varies year by year) within the Sacramento River watershed. With exceptionally productive years of 2006 and 2011, the overall electricity generation has a decreasing trend. Data source: EIA 2015.

To determine whether this can be traced back to decreasing rainfall amounts, the precipitation and electricity generation were tested for a mutual relationship. Correlating electricity generation data with precipitation on a month-to-month basis (Table 1), however, is not appropriate. Not only are the correlations not strongly significant, but they are generally negative. This would mean that the lower the precipitation levels, the higher the electricity generation outputs. The reason for this is that rainfall and its usage for hydropower generation does not – and physically cannot – happen on the same time scale. As Meadows et al. (2004) state, the response of lake and reservoir levels to precipitation can take

anywhere between three months and two years, depending on the surrounding geography, geology, vegetation and various other factors. Figure 3 shows historical monthly precipitation and electricity production patterns and the lag between the two is apparent.

Table 1: Correlations between precipitation and electricity generation in the Sacramento River watershed from the corresponding months for years 2001-2014.

Month-to-Month Correlation													
2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
-0.69	-0.28	-0.31	-0.39	-0.10	0.40	-0.55	-0.55	-0.51	-0.52	0.03	-0.48	-0.36	-0.55



PRECIPITATION – ELECTRICITY PRODUCTION

Figure 3: Time difference between precipitation and electricity generation increases and declines over the 14 year period show similar trend in both those variables. Sources: PRISM Climate Group 2015 (Precipitation); CEC 2015 (Electricity Generation).

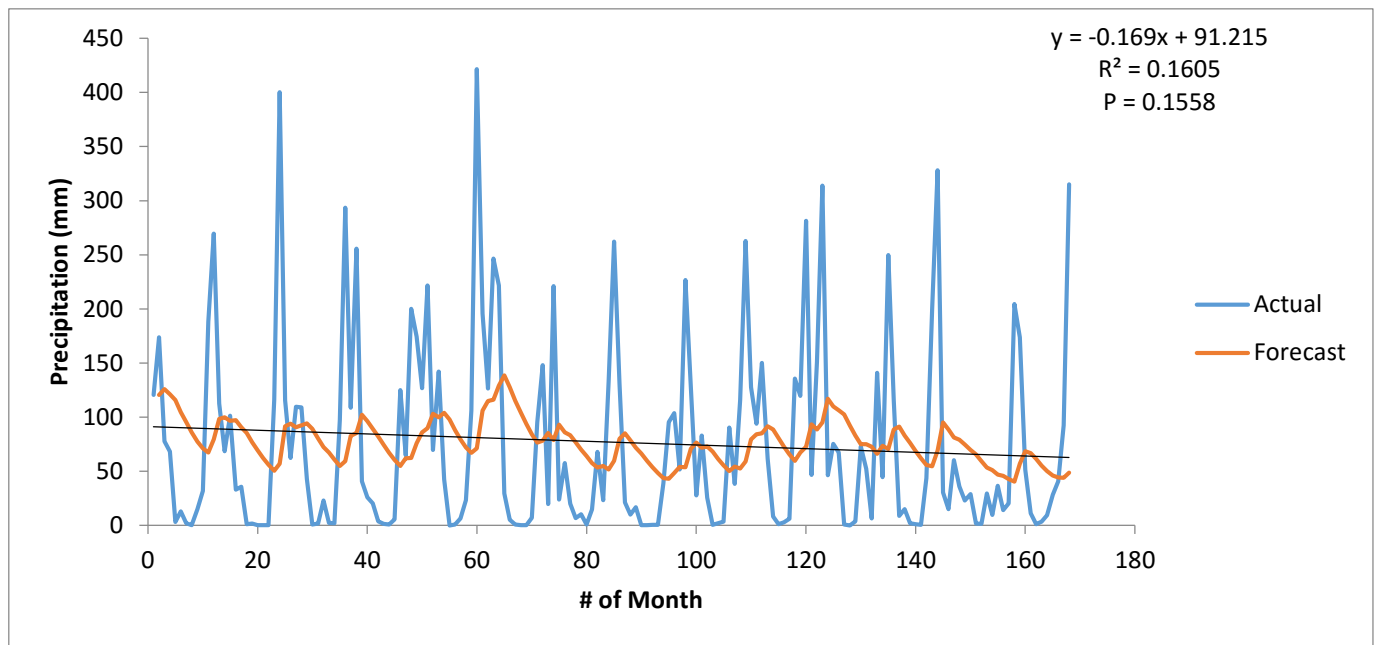
For the Sacramento, watershed, the time lag that produces the highest correlation results is six months. Since electricity production data after December 2014 are not available, only the precipitation

data for the first half of the year are used. Table 2 shows that the correlation is positive, but highly variable across years.

Table 2: Correlations between precipitation and electricity generation with a 6-months lag. A 6-months lag provided the highest, most significant correlation values, coupling January-July, February-August, etc.

6-Months-Lag Correlation													
2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
0.68	0.74	0.08	0.83	0.26	0.68	0.63	0.60	0.82	0.69	0.46	0.45	0.39	0.80

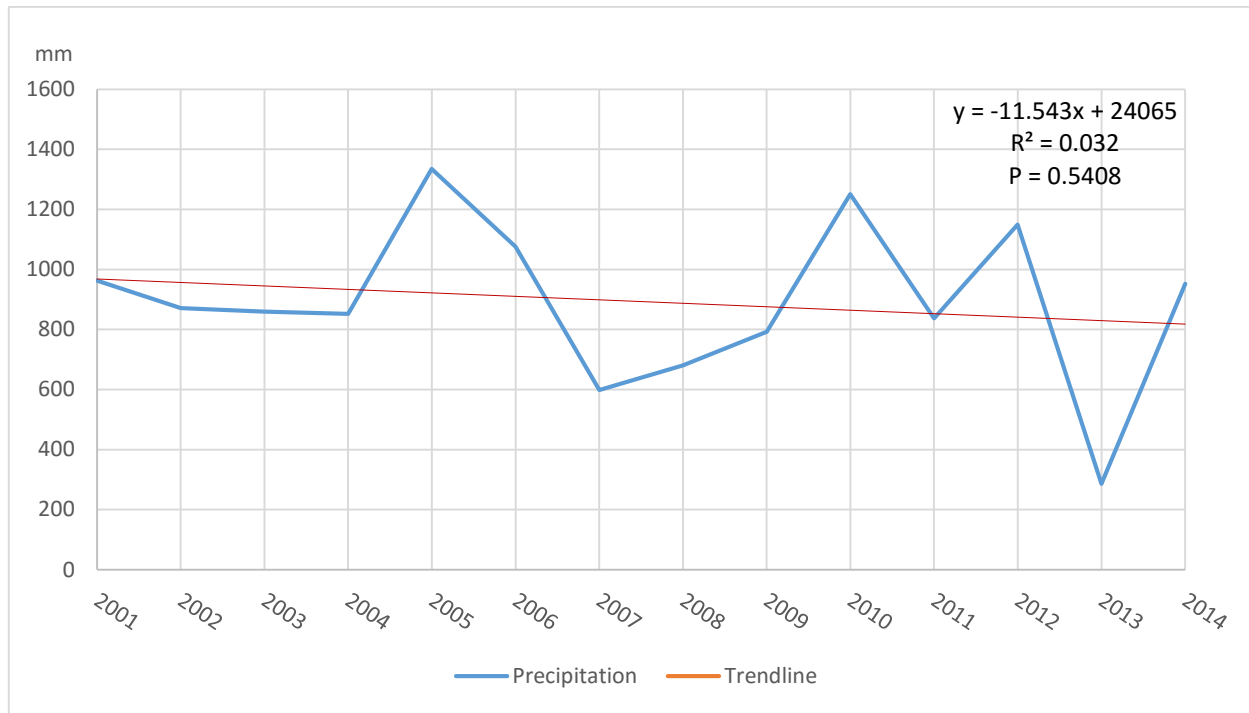
The problem with precipitation, especially in this region, is its high variability and seasonality. (See graphs with annual precipitation in the appendix). The monthly average precipitation amounts range from 0,00 millimeters per month through 421.6 millimeters per month, with the main rainfall season ranging usually from October to March. Due to the large range of precipitation values, it would be difficult to fit a trendline to the time series. Therefore, exponential smoothing has been applied to the dataset. Exponential smoothing assigns exponentially decreasing weights as the used data gets older, whereas newer data is being assigned progressively greater weight. At each point at which some data is recorded, an exponentially smoothed level is calculated which updates the previous level. In other words, exponential smoothing narrows the amplitude of the curve. This allowed for an easier, more obvious fit for the trendline.



EXPONENTIALLY SMOOTHED MEAN PRECIPITATION

Figure 4: Monthly average precipitation in millimeters over the Sacramento River watershed. The damping factor – which can take one values 0-1 – for the smoothing of this dataset was selected at 0.9, i.e. a fairly high smoothing level which eliminates peak values and enables better fit for a trendline. Source: PRISM Climate Group 2015.

From the graph in Figure 4 it is visible that the monthly precipitation values within the watershed did indeed decrease, from an average 96mm per month in 2001 to 61mm in 2014. To make this change even more clear, we can use the total mean annual precipitation values. Plotting the yearly data shows an annual decrease from 1000 mm to a little over 700mm per year.



MEAN ANNUAL PRECIPITATION

Figure 5: Annual mean precipitation recorded over the Sacramento River watershed. Source: PRISM Climate Group 2015.

However, it is necessary to keep in mind that not only is precipitation highly seasonal, but due to the very different physical geography across the watershed, it is also very regional. Thus, monthly data with great seasonal variability would not be appropriate to assess long term trends with a trendline. The trendline depicting the precipitation decline in Figure 5 is based on annual precipitation amounts. It appears that the watershed has been experiencing a time shift in precipitation, as well as a slight change in precipitation patterns, where extreme low precipitation periods are extending, but extreme precipitation events are more frequent. (See monthly precipitation graphs in the appendix). The graphs show that, while at the beginning of the measuring period most rainfall happened during fall and winter months (November, December, January), at the end of the study period the highest rainfall occurred later, in spring months (January, February, March). (See Table 3).

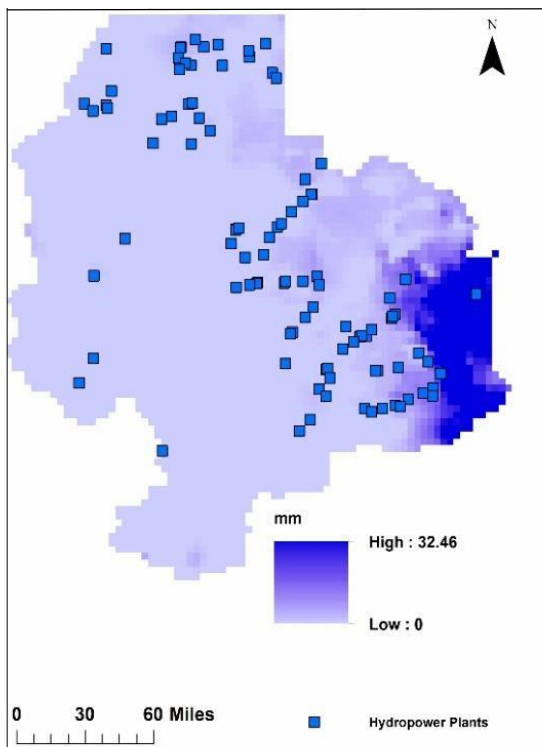
Table 3: Left: Highest precipitation month; Middle: Second highest precipitation month; Right: Third highest precipitation month. All values in millimeters. Source: PRISM Climate Group 2015.

YEAR	MONTH	PRECIPITATION (mm)	MONTH	PRECIPITATION (mm)	MONTH	PRECIPITATION (mm)
2001	December	818.43	November	575.29	February	508.55
2002	December	1529.39	November	441.91	January	321.35
2003	December	793.49	April	606.81	January	321.35
2004	February	712.65	December	595.48	October	313.13
2005	December	1462.65	March	542.57	May	476.77
2006	January	593.34	March	564.25	April	542.57
2007	February	573.32	December	437.19	October	333.24
2008	January	805.61	February	401.2	November	352.61
2009	February	686.18	March	413.43	October	358.69
2010	January	949.99	December	786.23	February	531.58
2011	March	814.31	February	417.41	May	282.11
2012	December	1026.84	March	765.17	November	649.32
2013	March	193.31	May	157.22	April	130.22
2014	December	892.74	March	531.31	February	524.14

MONTHS WITH MOST PRECIPITATION 2001 – 2014

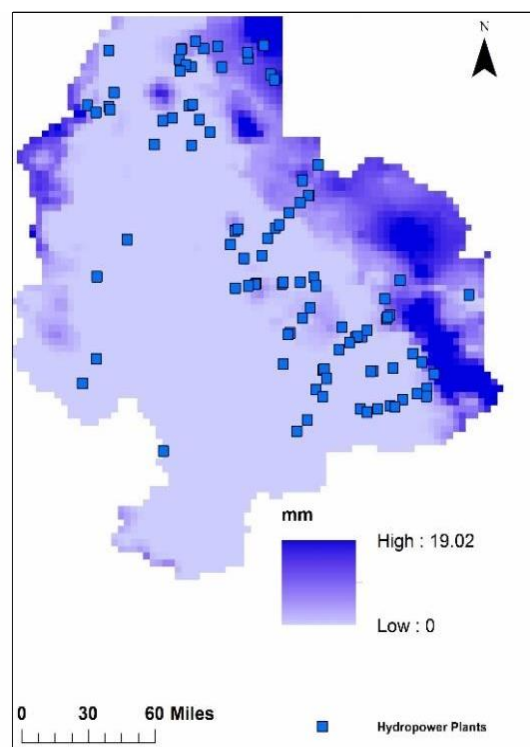
Mean precipitation is commonly used as the indicator for rainfall analysis in particular areas, whole states, or even entire countries, which greatly ignores the precipitation distribution and diversity in such places. The Sacramento River Watershed is a great example for this. Even though relatively small,

it includes the peaks of the Sierra Nevada with elevation of over 14,000 feet, the older, flatter and precipitation rich Klamath Mountains, as well as the arid Sacramento Valley. This diverse geography results in very heterogeneous dispersion of precipitation, which leaves certain locations without any rainfall for up to 4 months. To convey a sense of the spatial heterogeneity and temporal changes of rainfall, precipitation maps of the watershed from the last three years of the study period are presented in Figures 6-8.



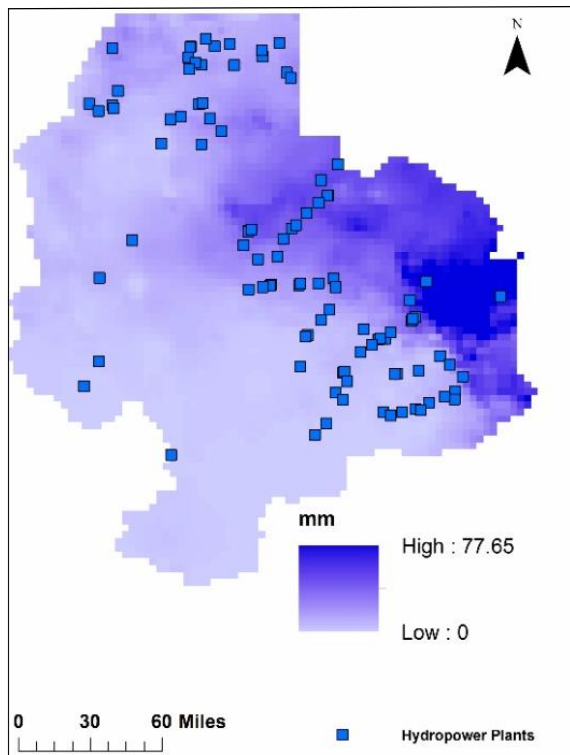
MONTHLY PRECIPITATION, AUGUST 2012

Figure 6: Source: PRISM Climate Group 2015



MONTHLY PRECIPITATION, AUGUST 2013

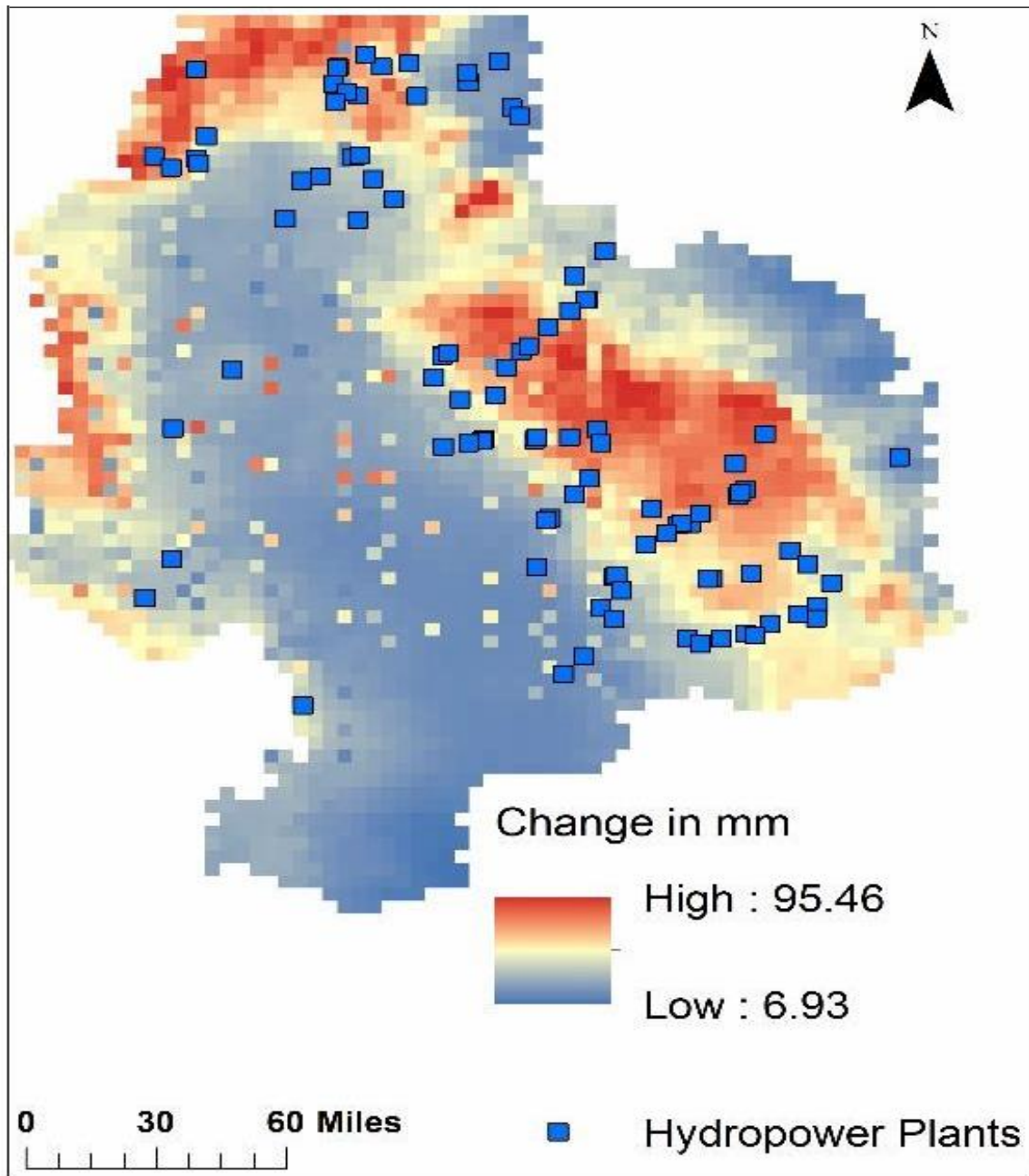
Figure 7: Source: PRISM Climate Group 2015



MONTHLY PRECIPITATION, AUGUST 2014

Figure 8: Source: PRISM Climate Group 2015

Precipitation maps for August were selected because in all 14 years August was the driest month of the year, with the highest mean precipitation of 23.11 millimeters in 2003. This however, was a very extreme value and standard mean precipitation for this month generally do not exceed 10 millimeters of rainfall. Figures 6-8 also show that the rain richest area of the watershed is the eastern south eastern part of the Sierra Nevada, which is also where a substantial number of the hydropower plants is located. Even though this area still receives the greatest amounts of precipitation of the entire watershed, it is in fact the region that is affected by changing precipitation the most (Figure 9).

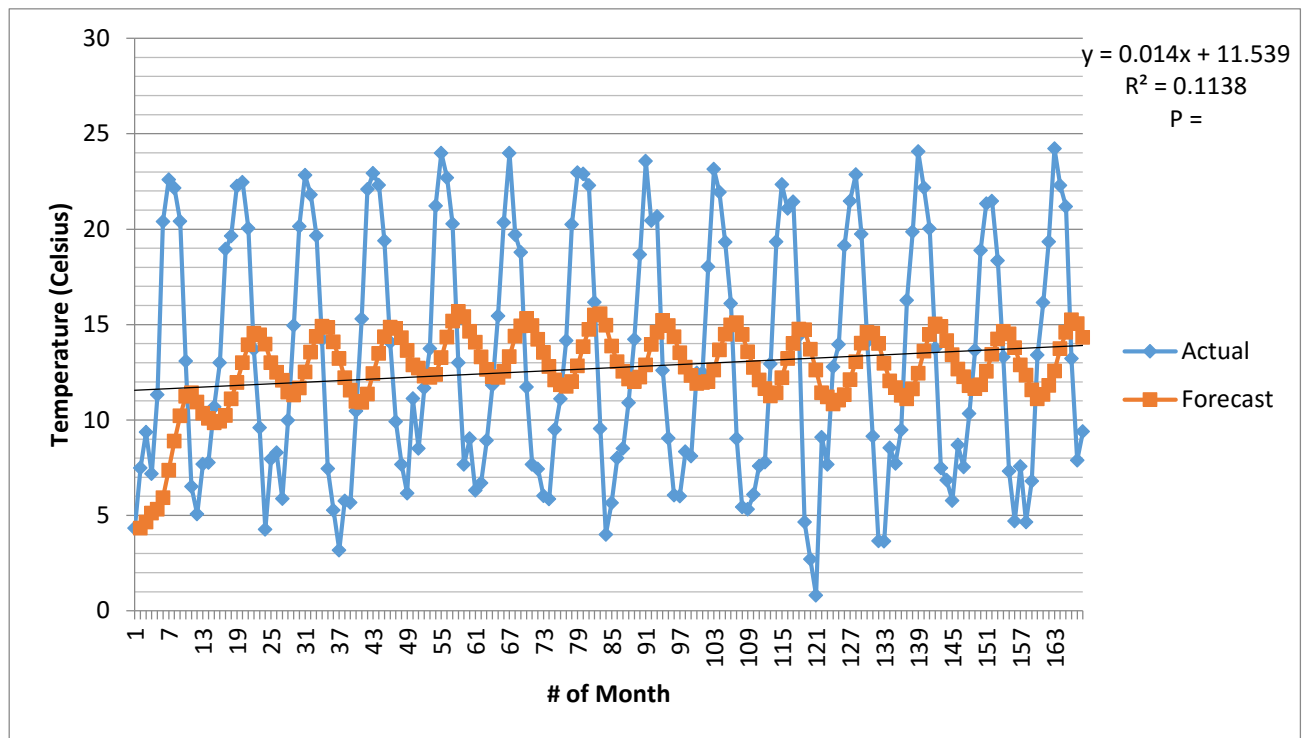


CHANGE IN PRECIPITATION 2001 - 2014

Figure 9: The Sacramento River watershed experiences both Mediterranean climate in most of its parts, and Alpine climate in the Sierra Nevada mountain range in the east of the watershed. While the areas in red fall into the Alpine climatic zone and receive more precipitation than the rest of the watershed, they have also experienced a greater decrease in average annual precipitation. Figure created using ArcGIS Software. Sources: PRISM Climate Group 2015 (Change in mm); CEC 2014 (Hydropower Plants).

Figure 9 depicts by how much average annual precipitation had declined over the span of the research period. While the already relatively arid region of the Sacramento Valley shows only minor change in rainfall, mean precipitation in the higher elevations decreases quite substantially. The graphic suggests that the mean precipitation value for year 2014 in Sierra Nevada, the Klamath Mountains and Trinity Alps, located on the western slopes of the Sacramento Valley, decreased by 95 millimeters compared to the year 2001.

Precipitation is only one of the two main climate variables that affect water availability in the prime hydroelectricity generating region. The second is temperature. As Duliere, Zhang and Salathe (2009) suggest, global temperature is likely to rise by 1-2 °C by 2050. On a longer time scale, for the state of California, it is suggested that there will be a temperature increase by up to 5.8 °C by 2100 (Cayan et al. 2008 and 2009). Regionally then the temperature growth might be even more significant. Generally, high elevation hydropower plans – which in the research area are significant in number and output – rely on snowpack and snowmelt runoff, respectively. An increase in temperature will change the snowmelt runoff patterns and might decrease the overall amount of water that is stored in form of snow in areas where snow has been accumulating for years. Similarly as with the precipitation means, computing and adding a trendline to the temperature means is rather uninformative due the large seasonal variations. Due to the Mediterranean climate in most of the watershed, and the Alpine climate in the Sierra Nevada, the mean temperature for the entire watershed ranges from 0.81 °C to 24.22 °C. However, local minima and maxima range from -8.94 °C to 30.75 °C. Thus, as it was the case with the precipitation trendline, the temperature means were smoothened in order to better fit a trendline – see Figure 10.



EXPONENTIALLY SMOOTHENED MEAN TEMPERATURE

Figure 10: Actual and exponentially smoothened average temperatures recorded over the Sacramento River watershed. Units in degrees Celsius. The large temperature amplitude is mainly due to two different climatic zones within the research area. Source: PRISM Climate Group 2015.

Increased temperature does alter snowmelt runoff patterns and thus affects water availability in reservoirs. However, modeling runoff and monitoring water levels in reservoirs goes beyond the scope of this thesis. Precipitation within the watershed seems to be undergoing more drastic changes than temperature.

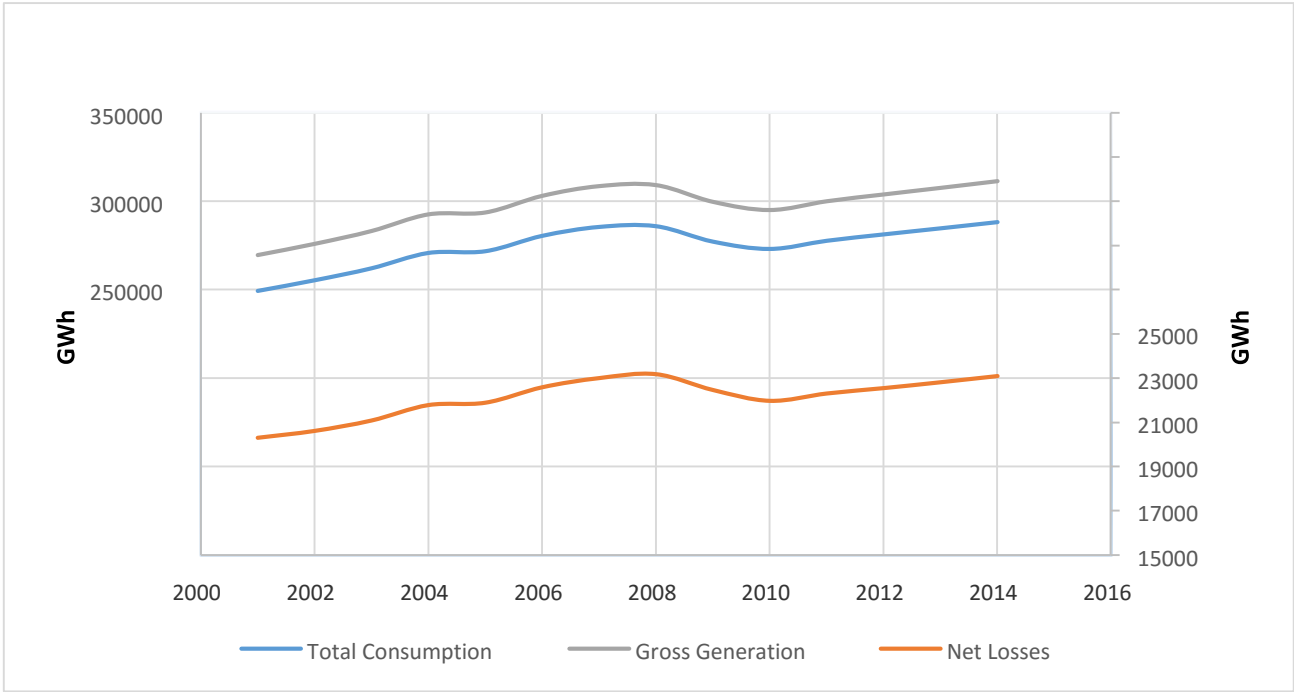
4.3 Significance of the watershed to California's electricity mix

The State of California is by far the largest producer of electricity on the Pacific coast. In 2012 alone it produced 2335 trillion BTU, which means California is the third produce of electricity largest among the western states – after Wyoming with 9611 trillion BTU and Colorado with 2921 trillion BTU (EIA 2015). This is not very surprising, considering that California is the country's largest state by population and second largest by economic size. Over the 2001 – 2014 study period, California's GDP went up from 10.56 trillion dollars to 17.31 trillion in current (2014) dollars, an increase of 63.9% within just 14 years (BEA 2015).

Therefore, it is not surprising that the demand for energy and electricity within the borders of California increased significantly as well. Figure 11 shows the development of electricity demand in California between 2001 and 2014. From 2001 the total consumption was continuously rising from the initial 249,303 GWh per year, up until 2008, when it reached the peak of 285,995 GWh per year. Significant drop in demand (and generation) occurred between 2008 and 2009. In this year the annual production went down to 273,103 GWh. This can be explained with the crisis and nearly-collapse of the world's financial system of 2008. The world's economies and industries suffered from a major recession, and California was not an exemption. In only those four quarters, California's GDP dropped by over 3 trillion dollars, or 2.9%. Luckily, the economy started to recover and grow soon after. Even though growth occurred at a lower rate than before 2008, electricity demand started to increase as well by 2009. By the end of 2014 the annual consumption reached 288,320 GWh, with a steady growth trend.

At the beginning of the measurement period, the net energy loss from the Californian grid was somewhere between 7-8%, as visible in Figure 11 (7.52% in 2001). However, there are efforts to minimize the occurring losses from the energy network. The state is investing large sums to modernize its electric grid. One of the ways to do this is by implementing smart grid technology. Smart grid is a

modernized electrical grid that uses digital “communication” between the supplier and the customer, and the data obtained from the network enables utilities to automatically respond to quick demand changes. This leads to a higher efficiency in electricity distribution, quicker restoration of electricity supply after disturbances, reduced peak demand etc. (DOE 2015) According to the Smart Grid Policy Center, in 2013 California was the most successful U.S. state in integrating smart grid technologies (Marcacci 2013). Within the 14 year study period, California was been able to reduce the net loss from 7.52% in 2001 to 7.39% in 2014. While this is not a very significant change in relative terms, this difference is substantial in absolute terms particularly given the growth in demand.



Electricity Demand

Figure 11: Annual average electricity demand in the state of California. Units in gigawatt hours. About 7 percent of the total instate electricity generation goes lost in transmission and distribution lines. Source: DOE/EIA 2015.

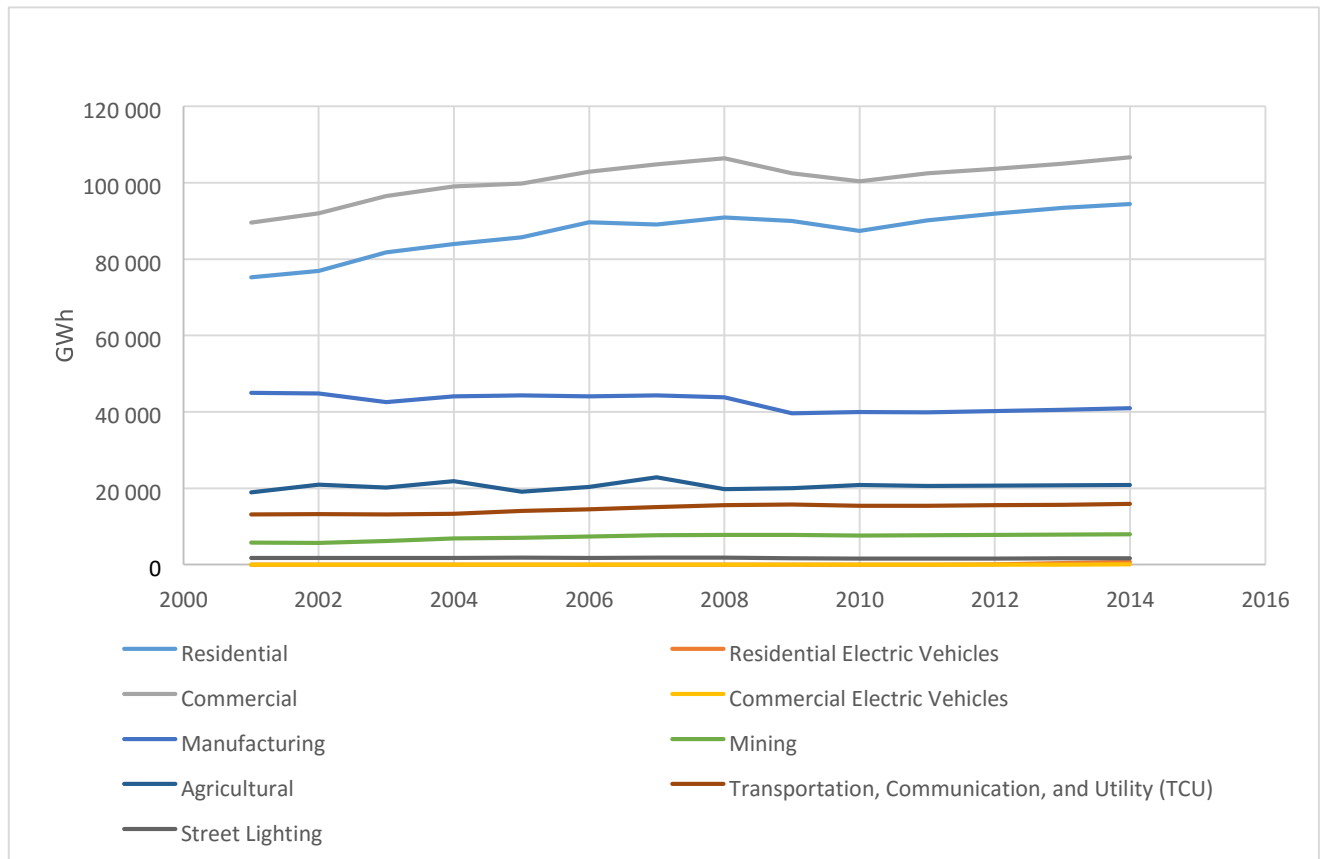
4.3.1 Electricity Consumption by Sector

Compared to other states in the western region, California has a relatively high consumption in the residential sector. While all surrounding states (AZ, NV, OR) consume between 24% - 28% in the residential sector, in California this sector consumes over 33% of all electricity produced (EIA 2015). At the same time, electricity consumption in the residential sector has been steadily growing during the study period, from 75,191 GWh in 2001 to 94,444 GWh in 2014, which is a 25.6% increase. This sector and the commercial sector are the two by far largest consumers of electricity in the state. With respect to how the economy evolved over the same period of time, and how the overall wealth grew, some growth in electricity consumption could be expected. Another, more significant factor is population growth. Between 2000 and 2010 Californian population grew from 33,871,648 to 37,253,956 – exactly a 10% increase, while the increase in consumption was slightly above 25%.

The recession in 2008 caused a decline in nearly all economic and production sectors. In some sectors, however, this drop was more visible than in others. While consumption in the residential sector dropped by less than 3.8% between 2008 and 2010, the decrease in the commercial sector was almost 6%. After two years the markets recovered and consumption in both residential and commercial sector started to rise again, although the rate of increase in the commercial sector was not as rapid as in the residential sector.

The third largest electricity consuming sector is manufacturing. Although being relatively consistent throughout the entire research period, a minor decline in electricity consumption was noticeable, as shown in Figure 12, consumption went from 44,986 GWh in 2001 to 40,939 GWh in 2014. The remaining sectors (Agricultural, Mining, Street Lighting, Residential/ Commercial Electric Vehicles, TCU) are very stable throughout the entire period. Yet, one notable change is the emerging use of private electric vehicles. Up until 2009, there were no records of electricity being used for recharging of

Residential Electric Vehicles. With new technologies and higher competitiveness on the market, the number of electric vehicles seems to be growing almost exponentially. Within only five years the electricity usage for this purpose went up from zero to 753 GWh. In terms of vehicles, according to the California New Car Dealer Association, in the year 2010 300 all-electric cars and 97 plug-in hybrid vehicles were registered. In 2014 29,536 new all-electric cars and 29,935 new plug-in vehicles were registered, totaling a fleet of 129,470 electric powered vehicles (CNCDA 2015).



Electricity Consumption by Sector

Figure 12: Annual average consumption by sector. Despite the growing prices per kilowatt hours in the residential and commercial sectors – as displayed in Figure – these two sectors have the highest, and most steadily growing electricity consumption. Source: EIA 2015.

4.3.2 Electricity Production by Source

Since California is one of the largest electricity consumers in the US, it is important to understand what electricity Sources is uses, for both economic and environmental reasons.

The clear leader in electricity production is natural gas. As of 2014 there were 243 power plants powered by natural gas in California. In the same year, these plants generated 121,855 GWh. The second largest amount of electricity is being produced by hydropower. Both electricity sources, however, are facing emerging issues. Even though natural gas is the largest source of electricity, unlike many other states California has to heavily rely on imports of natural gas. The in-state production in 2014 was only about 10 percent, and declining. In 2001 imports accounted for over 15 percent. The gas supply comes to California from four major regions – Canada (16%), Southwest (38%), and Rocky Mountains (36%) (Rhyne Gonzales 2014). Most imports get into the state via interstate pipelines.

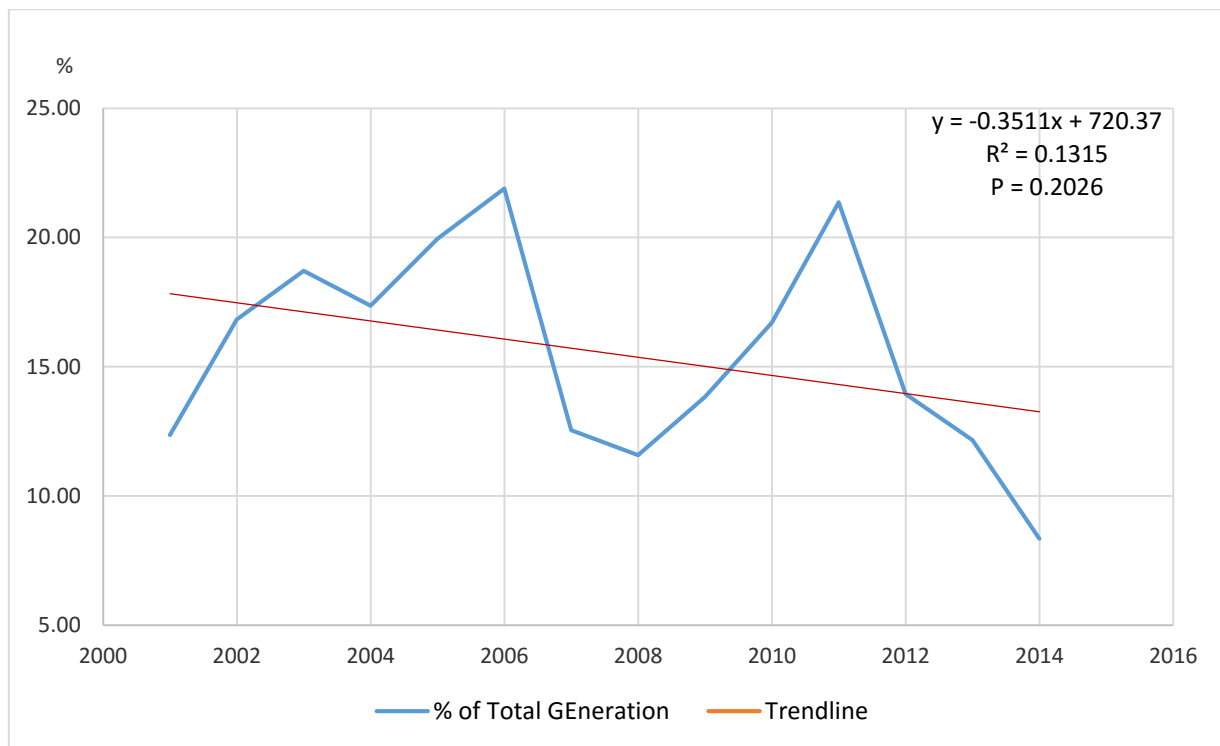
Demand for electricity in California has been increasing and currently there are no indicators that this will change in the near future. Because of AB 32 and in the 2002 Renewable Portfolio Standard (RPS) Program, which sets the goal to produce 20% of the overall electricity supply from renewable resources by 2017, later modified to 20% by 2010, California relies on a mix of natural gas and renewables for its electricity generation. Electricity from natural gas-fired power plants is rather clean in terms of CO₂ emissions and pollution in general, cheap to operate (aside from the capital costs), and safe. In 2014, over 45 % of the in-state produced electricity came from natural gas power plants (CEC 2015). However, renewables will have to play a larger role in the future -the RPS goal for 2020 is to generate 33% of the in-state produced electricity mix from renewable resources.

California is the third largest hydropower producer on the west coast, and the fourth largest producer nation-wide – after Washington, Oregon, and New York. In 2014 hydroelectric facilities generated 16,447 GWh, which was a historic low. Hydroelectricity generation is subject to seasonal

precipitation and snowmelt runoff. Thus, electricity production in this sector fluctuates like in no other sector. However, hydroelectricity generation has been showing declines over the past few years, which can be linked to droughts that have been plaguing the state. This is very problematic in the face of the RPS, since hydroelectricity has always been counted in as a major renewable contributor to the electricity mix. If this sector will keep declining, the state will face serious issues meeting the 2020 goal.

There are new emerging renewable electricity sources that could make up for the loss in hydropower. Within the 14 years of the study period, solar and wind power have boomed. The growth in wind energy was more or less steady – from 3,242 GWh generated in 2001 to 12,908 GWh in 2014, with an increase in generation by few hundreds of gigawatt hours every year. Solar power, however, was nearly non-existent in 2001. Electricity generation from solar skyrocketed after 2012, from 836 GWh in 2001 to 1,097 GWh in 2011, to 4,287 GWh in 2013, and 10,365 GWh in 2014. However, the intermittent nature of both energy sources makes them problematic for base load power generation, for which hydropower is often used.

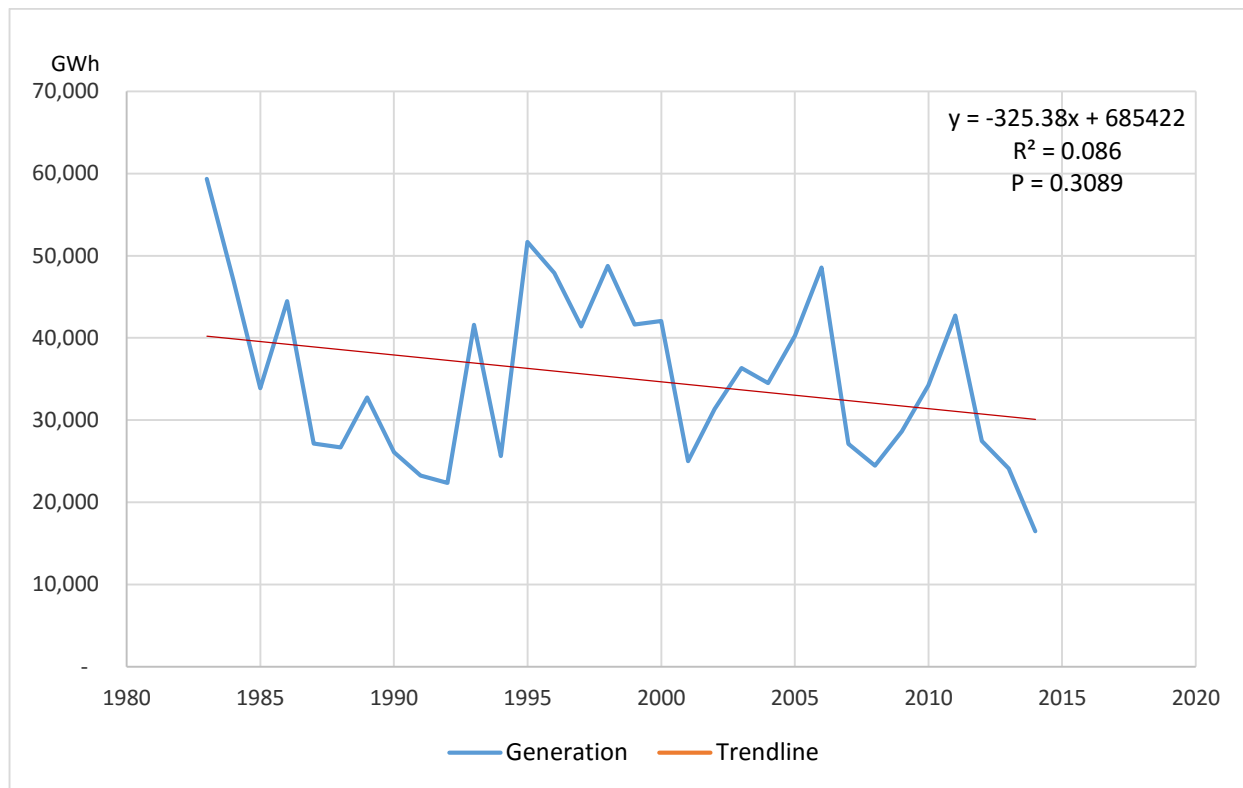
On average, hydropower was covering little over 15% of all electricity demand in California between 2001 and 2014. However, hydropower availability depends strongly on the climatic conditions in given area, which can make the year to year generation vary a lot. In good, wet years hydropower was responsible for over 20% of all in-state generated electricity, in other years it was barely above 10%. The smallest share that hydropower had on the overall electricity supply was the extremely dry year of 2014, only 8.35%. Although it can be argued that historically there had always been a significant drops in hydroelectricity production in one or two years. The California Energy Commission provides hydroelectricity production data since 1983. Based on this data it is clearly visible that the production trend has overall been in decline for the past 30 years. The 14 years trendline in Figure 13 shows a clear decrease in the percentage of electricity generation from this source within California.



Total Generation from Hydropower (%)

Figure 13: Despite two hydropower generation peak years – in 2006 and 2011 – the overall trend is declining. In Figure 3 is displayed the precipitation curve for the observation period, which shows very similar trends. Source: DOE/EIA 2015.

Overall, however, the significance of hydropower as a fraction of total electricity generation capacity has been declining. It can be argued, however, that the percentage decline of electricity from hydropower is caused not primarily by the share of hydropower getting smaller, but by emerging of new electricity sources and technologies such as wind and solar energy. And yes, these new sources are playing a more and more important role in California’s energy mix – especially solar power generation skyrocketed since 2011 – but the overall share remained, as of 2014, below 8%. This becomes even more apparent if we look purely at the GWh data from hydropower generation trendline in Figure 14 for the entire period for which California Energy Commission made the data available (1983 – 2014).

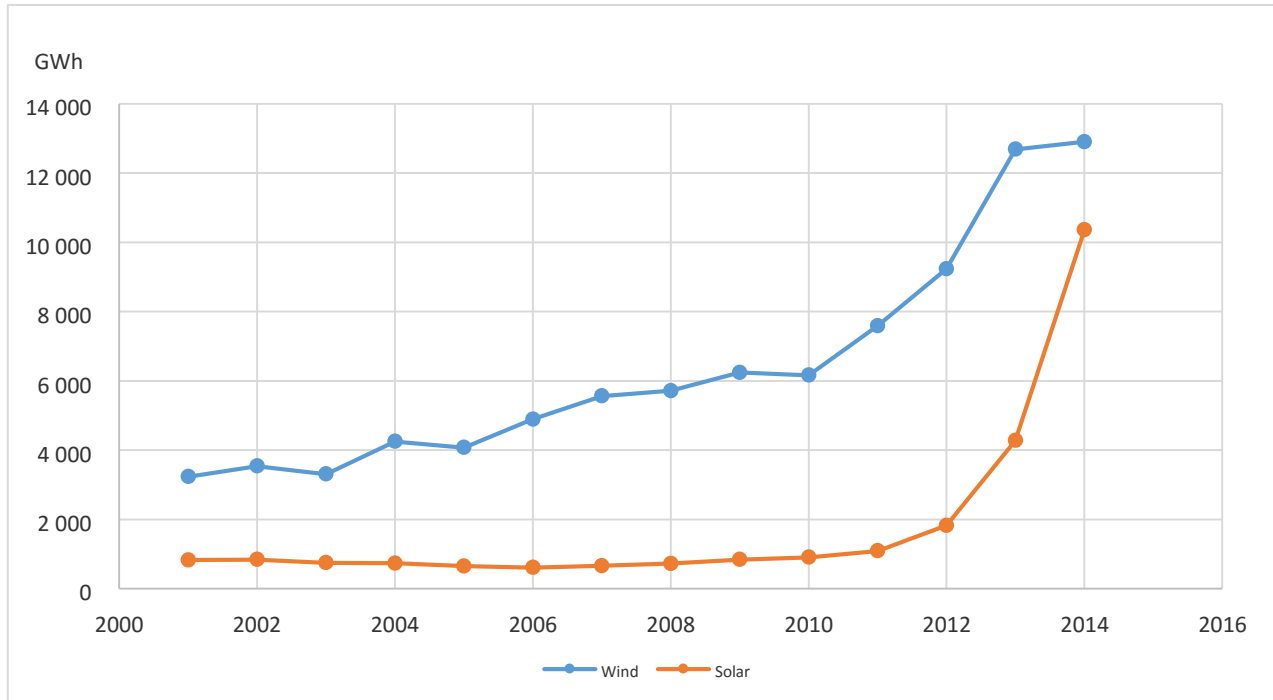


TOTAL GENERATION FROM HYDROPOWER (in GWh)

Figure 14: California annual hydropower generation from 1983 to 2014. The trendline indicates that decline in hydropower generation has been an ongoing problem that exceeds the 14 year research period. Source: DOE/EIA 2015.

One factor is the obvious setback in water availability and the associated reduced electricity generation. The other factor is that it is nearly impossible to add more generating capacity, simply because most suitable streams have already been built up. On smaller streams private, low capacity power generating facilities can possibly be setup, but those would fall maybe into small hydro, but more likely into micro hydro category. Micro hydropower generating units usually generate under 100 kW and are mostly used to provide electricity to isolated homes or communities, depending on the size of the unit. In some cases these micro hydro facilities are connected to the grid as well, especially if in that particular net metering is offered (EERE 2013). But there is another reason why hydropower share in the production from renewables is dropping as well. Especially over the past couple of years the percentage

of electricity produced from solar and wind went up dramatically. Wind energy had been on a steady rise since the early 2000's. Solar energy on the other hand sky rocketed after 2010. Combined those two “new” sources added over 23,000 GWh, which is comparable to the output generated in the Sacramento River watershed in wet, productive years (Figure 15).



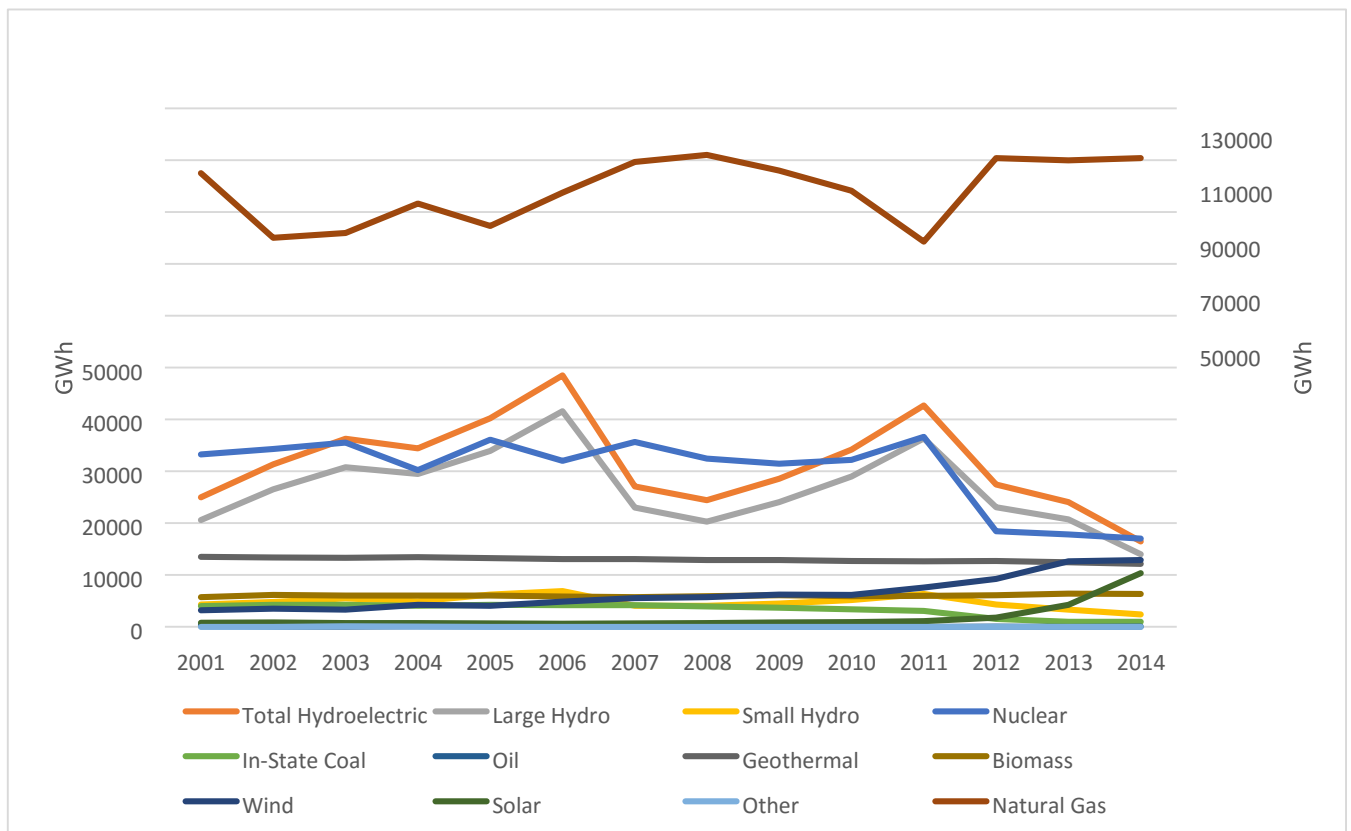
Wind & Solar Energy (GWh)

Figure 15: Due to the RPS goals, as well as other California state incentives encouraging and subsidizing solar power, installation of photovoltaics in both commercial and private sector started to grow rapidly, generating over 10,000 GWh in 2014. Source: CEC 2015.

Lastly, there is a significant fraction of electricity produced from nuclear energy. In fact, nuclear energy has been steadily the number three source of electricity, up until 2014 when it actually surpassed hydropower. Within the last few decades, California decommissioned or dismantled most of its nuclear power plants. For over a decade, the last two nuclear power plants were supplying between 32,000 and 37,000 GWh every year, until January 2012, when the San Onofre power plant was turned off due to a

leak inside of its steam generator. This caused the drastic drop in electricity production from nuclear energy between 2011 and 2012 evident in Figure 13, from 36,666 GWh to 18,491 GWh.

Other electricity producing sectors are generally stable throughout the whole study period, and some do not contribute crucial amounts of electricity to the grid. Electricity generation from oil has been oscillating between 110 GWh and 50 GWh per year. Geothermal energy has been producing between 13,500 GWh and 12,000 GWh every year, even though it shows a slightly declining trend. Biomass has been producing slightly less than a half of what geothermal energy generates. The annual generation from this source has been between 5,700 GWh and 6,400 GWh without any clear increasing or decreasing trend.



ELECTRICITY PRODUCTION BY SOURCE

Figure 16: Hydropower had been continuously the second – or third, depending on each year’s precipitation conditions – most productive source of electricity. While natural gas-fired power plants generate four times more electricity a year on average than hydropower, they rely on natural gas imports from out of state. Source: CEC 2015.

4.3.3 Suppliers

Generally, the electricity is generated by two kinds of suppliers – privately and publicly or investor owned utilities. Out of the over 200,000 GWh of in-state generated electricity, 184,000 GWh were produced by Investor-Owned Utilities (IOUs), publicly owned Load-Serving Entities (LSE), and electric cooperatives (Smutny-Jones 2013). The other 16,000 GWh were produced by private suppliers, also called independent power producers (IPP). IPPs, as defined by the California Energy Commission, generate power that is purchased by an electric utility at wholesale prices. The utility then resells this power to end-use customers. The most common types of private electricity generation cogeneration are private businesses, small-scale privately owned wind and hydro turbines etc. Cogeneration is mostly used by the refining and food processing industries in order to maximize the energy efficiency of consumed natural gas and other fossil fuels. With the technology improving and prices for installation getting more affordable, over the past several years electricity production from private photovoltaics has started to increase quite rapidly, from a mere 16 GWh in 2001 to 2,600 GWh in 2014, as seen in Figure 14.

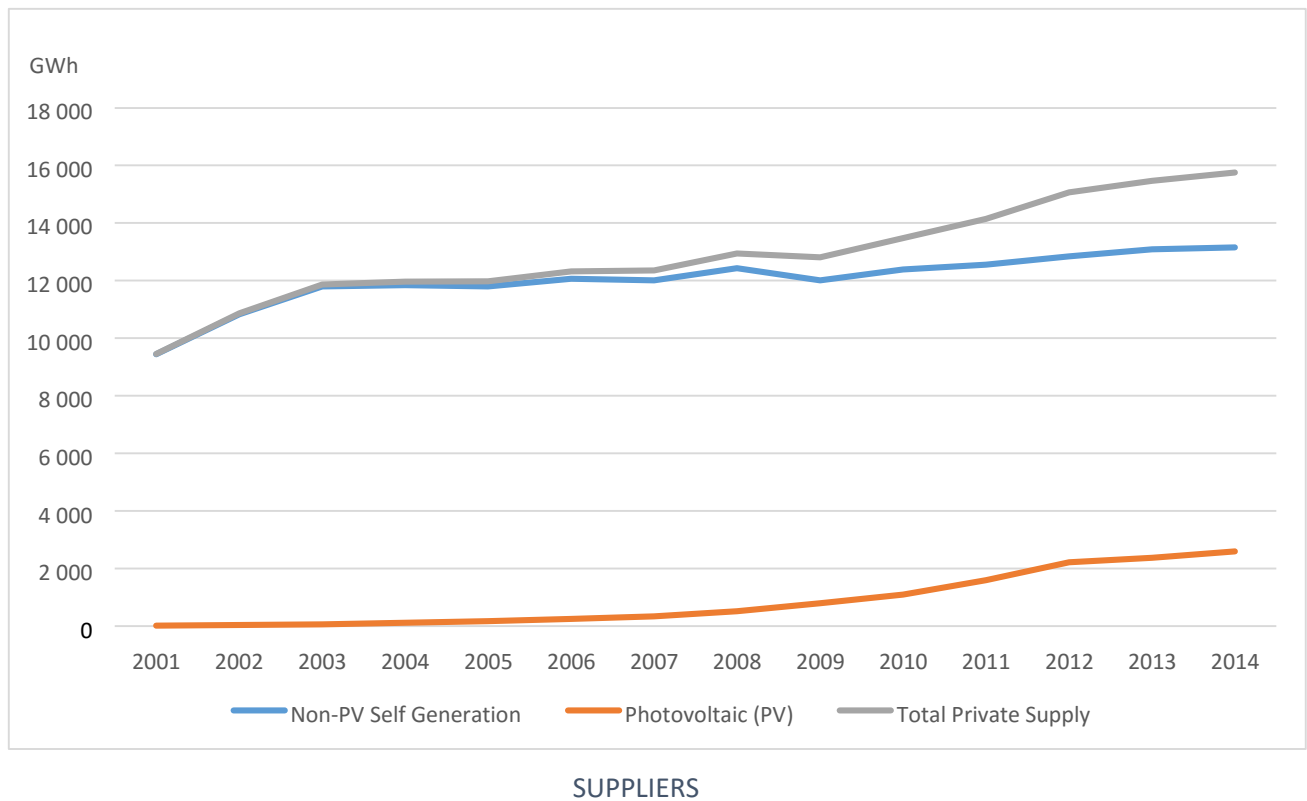
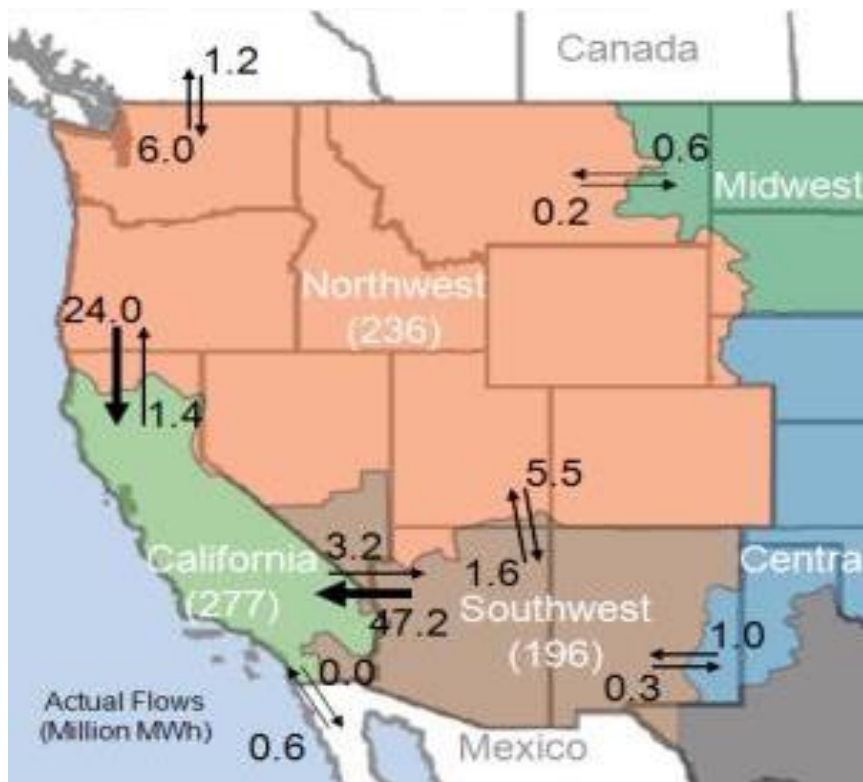


Figure 17: Growth of total generation and private generation from photovoltaics. Source: CEC 2015.

4.3.4 Electricity production by location

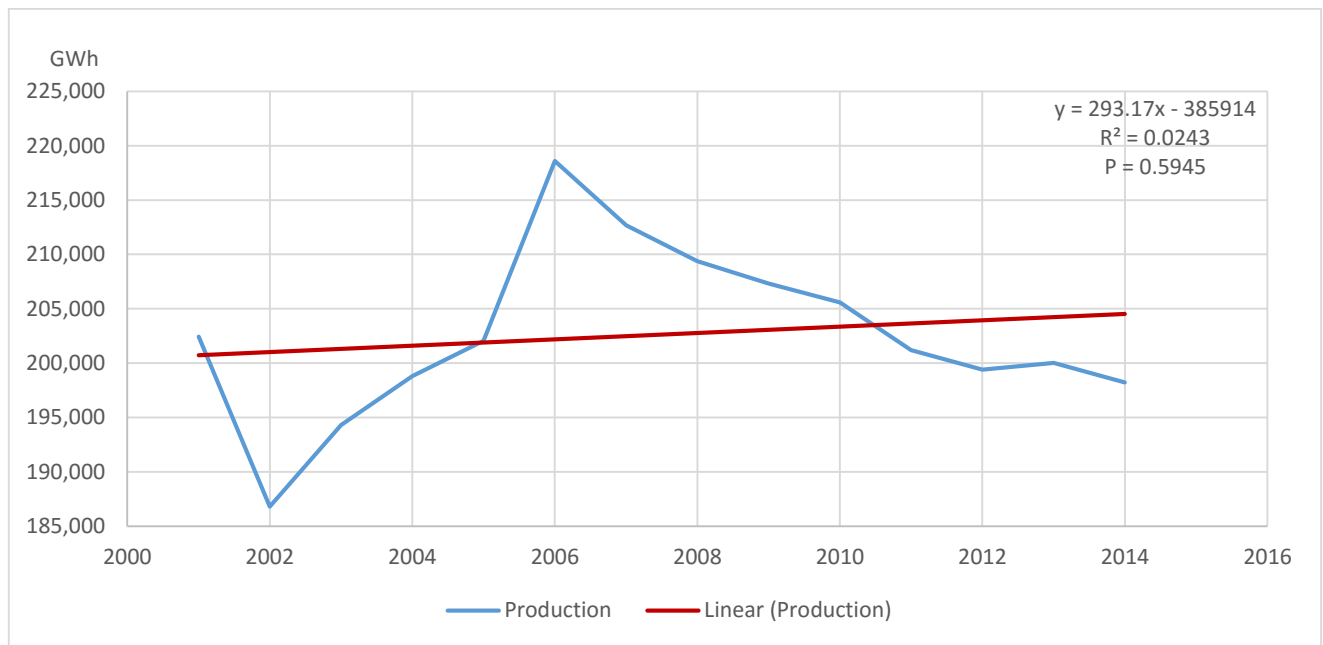
In 2013, the state of California was the second largest consumer of electricity in the United States, right after Texas (EIA 2015), and the state produced 67.4% of electricity within its borders. Overall, during the 14 year study period, in-state electricity production was usually between 68% and 72%— with a maximum of 75.7% in 2001 and a minimum of 65.9% in 2012. This means that historically California has had to import about one third of the electricity it consumes every year. This imported electricity comes from the Northwest (OR, WA, ID, MT, WY, CO, UT, NV – ca. 10%) and the Southeast (NV, AZ, NM – 20%) (EIA 2011). The exported electricity amounts are rather small fractions compared to the imports. Figure 15 displays the amounts of imports and exports between the individual states in 2010 and the electricity transfers ratio between the Northwestern and Southeastern region. These are significantly smaller than what is being sold to California.



ANNUAL NET POWER FLOWS RECEIVED AND DELIVERED IN THE WESTERN UNITED STATES

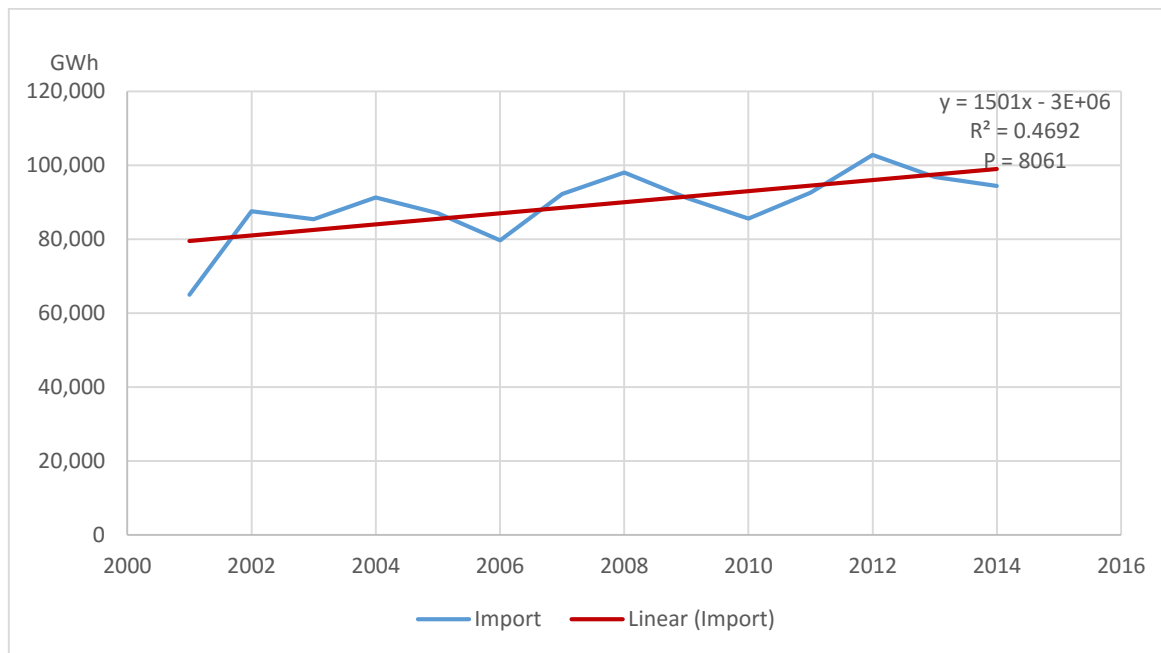
Figure 18: California imports about 1/3 of its annual electricity demand. The two main import regions are Northwest and Southwest. While majority of the electricity from the Southwest is generated from fossil fuels, the Northwest imports are mainly from renewable resources – especially hydropower from Oregon and Washington – and therefore comply with California’s RPS. Source: EIA 2013.

Graphs 10 and 11 represent the total in-state electricity generation amounts and imports between the years 2000 and 2015. The steep drop in in-state generation (Figure 16) between 2000 and 2002 – and inversely the quite significant rise in electricity imports (Figure 17) – are the results of the 2000 and 2001 California energy crisis. The energy crisis was caused by illegal market manipulations by the energy consortium Enron, and it essentially caused a shortage in electricity supply, black-outs, spikes of electricity prices to triple of the previous levels and a breakdown of the, until then, deregulated market. The state suddenly could not supply nearly close to sufficient amounts of electricity and had to start buying and importing substantial percentages from neighboring states (Sweeney 2002).



TOTAL IN-STATE ELECTRICITY GENERATION

Figure 19: *The in-state electricity generation hit a historic minimum during the 2000/2001 California electricity crisis. After reaching the peak production in 2006, the in-state generation started experiencing a decline, predominantly due to the newly introduced clean energy policies. Source: EIA 2015.*



NET ELECTRICITY IMPORTS IN GWh

Figure 20: Due to the continuously growing electricity demand, accompanied by the decline of in-state generated electric power caused by closing several nuclear and coal fired power plants, as well as the decline in hydropower generation, the net electricity imports have been growing steadily. Source: EIA 2015.

The peak production was reached in 2006, after which a continuous decline in in-state generation started. This is linked to the signing of AB32, which caused the closing down of California's coal fired power plants and shifted production of the majority of in-state generated electricity to natural gas. At the same time, California is number two in electricity production from renewable resources, after Washington. This is mostly possible thanks to very significant amount of hydroelectricity that California produces.

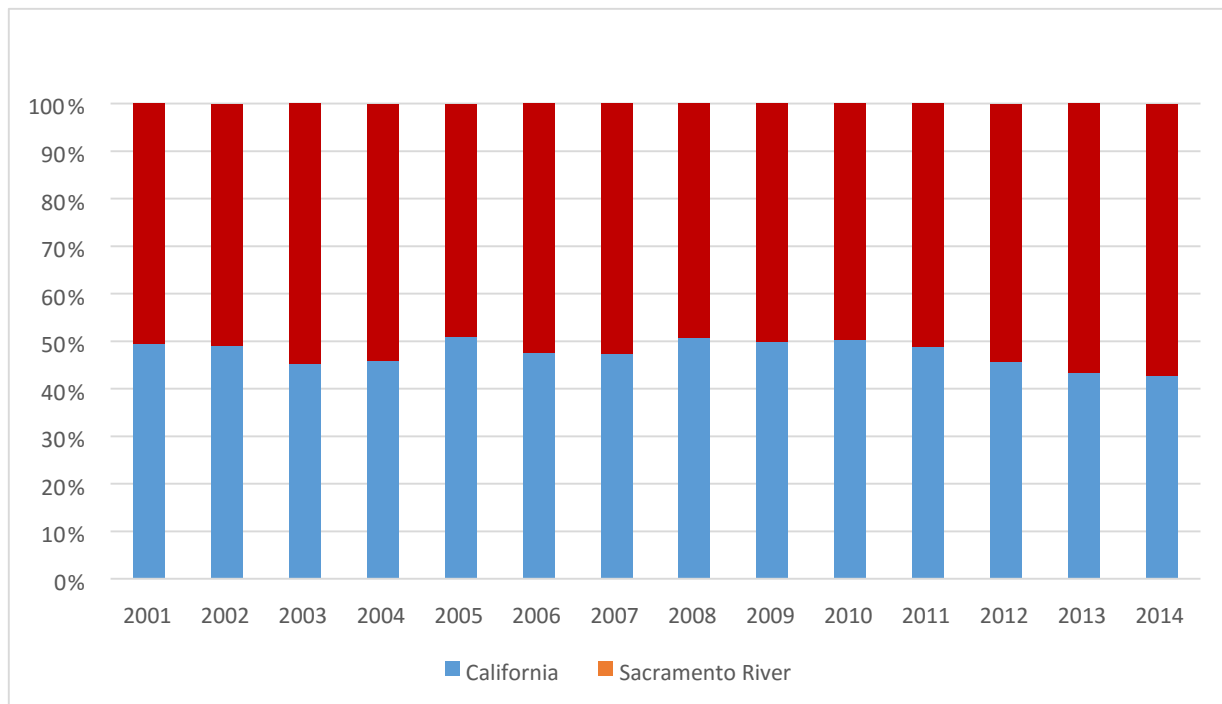
Since this paper is concerned with the Sacramento River watershed, the question is – what role does this area play on the state level? The watershed of the Sacramento River is home to the largest accumulation of hydroelectric facilities, both large and small, in the state. It includes major river systems, such as the Upper American River, Sacramento River or the Feather River. Out of the over 260 hydropower plants in California almost a hundred is located in those 17 counties, including some of the

largest hydroelectric dams such as the Edward C. Hyatt, Shasta, Chicago Park and many others.

Correspondingly, a large amount of electricity is being produced in this comparatively small area – the entire watershed of the Sacramento River drains an area about 1/6 of the state. The total producing capacity varies slightly year to year, depending on what facilities had to be shut down for the particular year. The installed capacity within the watershed, however, is a little under 5,700 MW. But just like in the rest of California, the number of hydropower plants that are online is not constant and several of them had to be shut down in certain years. The temporary – even though maybe frequent – shutdowns concerns seven power stations.

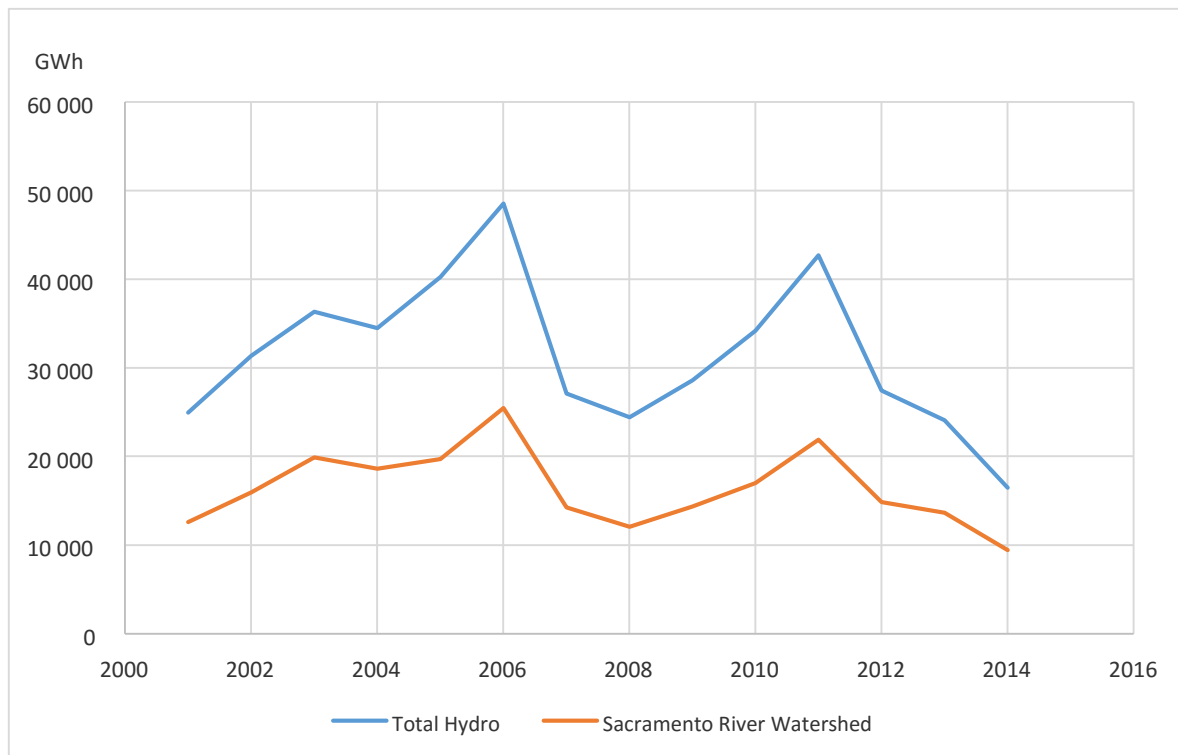
All hydroelectric facilities in the area are owned by 22 different operators, with the major ones being the Sacramento Municipal Utility District (SMUD), Pacific Gas & Electric (PG&E), and United States Bureau of Reclamation. Other operators are commonly county-level agencies such as the Nevada Irrigation District, Placer County Water Agency or El Dorado Irrigation District, and few small private companies operating small hydro facilities.

California's electricity generation from hydropower can vary, depending on the precipitation conditions that particular year. What remains rather constant, however, is the role of the Sacramento River watershed for the state's hydroelectricity generation. Even though the watershed is home to "only" about a fifth of California's hydropower facilities, it steadily produces about a half of all California's hydroelectricity combined. In other words, California's hydroelectricity generation potential directly depends on the Sacramento River Watershed. Even in the year 2005, which was percentage wise the weakest, the watershed generated 49.03% of the state's hydroelectricity. Due to the drought, generation from hydropower started to drop rapidly in 2011, up to the historic low in 2014 when 16,477 GWh were produced from all hydroelectric facilities combined. The Sacramento River watershed facilities accounted for 57.22% - 9,429 GWh of the total production (Figures 21&22).



% OF HYDRO ELECTRICITY FROM SACRAMENTO RIVER WATERSHED

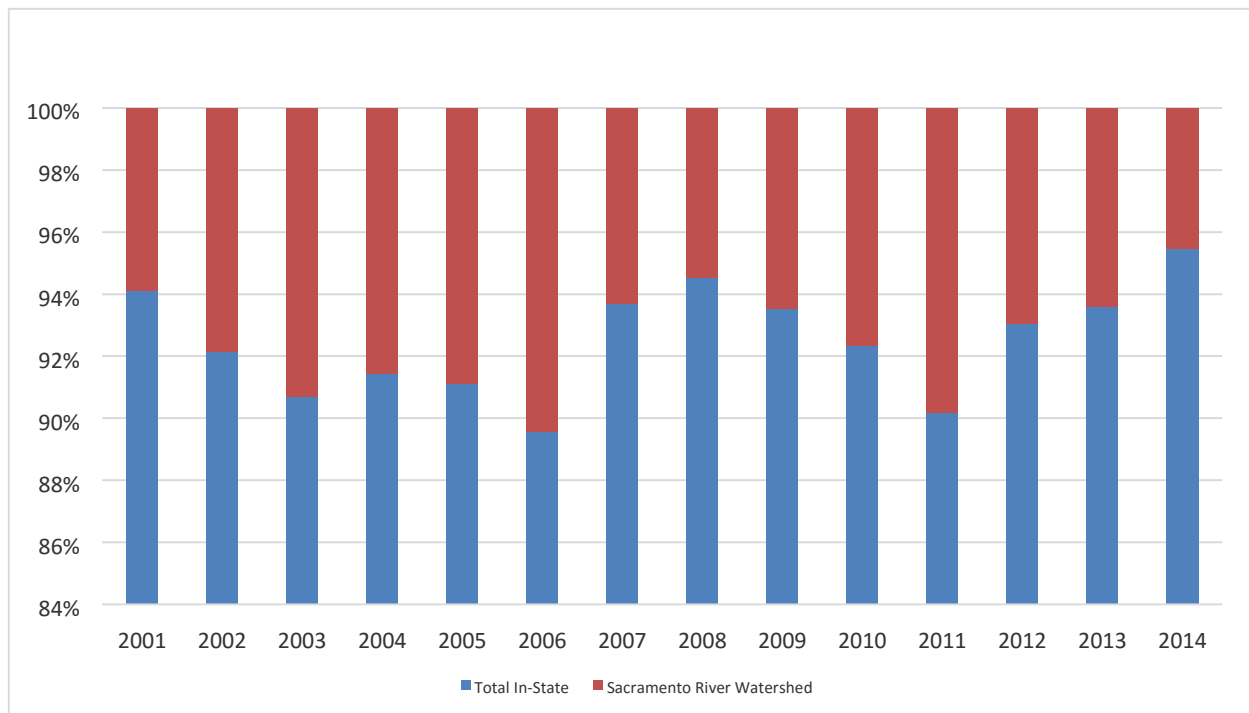
Figure 21: The 95-99 hydropower plants are generating over 50 percent of the state's total hydropower generation. The watershed's significance grows even more during California's dry year, when it supplies close to 60 percent of all in-state hydropower. Source: EIA 2015.



TOTAL & SACRAMENTO ELECTRICITY GENERATION IN GWh

Figure 22: Proportional electricity generation trends on both California level and Sacramento River watershed level demonstrate the states dependency on the research area. As shown in Figure 21, the gap between the total in-state hydro generation and the watershed's generation decreases especially during dry years. Source: EIA 2015.

In 2014 California total energy mix operated with 296,843 GWh. About one third of the energy originated outside the state's borders. 37,261 GWh was imported from the northwest, 60,609 from the southwest, as can be seen in Figure 15. This leaves the total in-state power generation of 198,973 GWh. Hydropower generally supplies between 10-13 percent to the energy mix, even though years where it supplied 17-20 percent were not rare either over the past 14 years. In the production-wise worst year so far, 2014, California's hydroelectricity facilities generated over 8 percent of the total power mix. With the Sacramento River watershed steadily generating between 48 and 52 percent of all in-state hydroelectricity, it was generating about 10% of all in-state energy, as seen in Figure 23.



SACRAMENTO WATERSHED PRODUCTION WITHIN CA (in %)

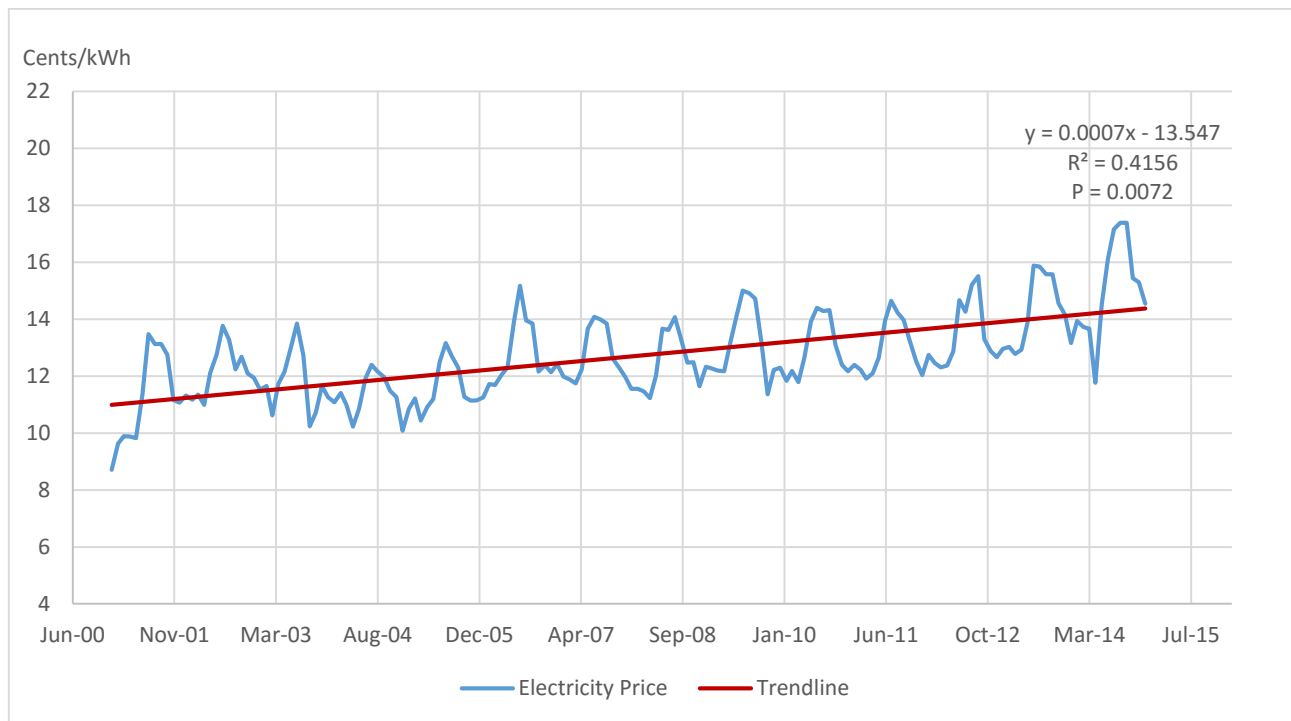
Figure 23: As hydropower is highly dependent on each year's climatic conditions, each year's electricity production can vary considerably. While in some year the Sacramento River watershed can supply over 10 percent of the overall in-state generated electricity, due to the shortfall in precipitation in recent years the watershed's share in total in-state generation fell under 5 percent. Source: CEC 2015.

The results show the clear connection between precipitation amounts and electricity generation within the Sacramento River watershed. Despite its size, the watershed's contribution and importance to the California's total hydroelectricity production is major, and the state's increase or decrease in overall hydroelectricity generation directly correlates with generation in the watershed. It is therefore of principal importance to either prevent the stored water from being treated uneconomically, or – in case water storage and conveyance cannot be improved on – find an alternative renewable resource that will be able to cover those up to 15% that is on average being generated on the Sacramento River and its tributaries.

4.4 Effects of the watershed's electricity production on electricity prices

Seeing the importance of the watershed to California's electricity mix the question whether the watershed's productivity affects electricity prices as well suggests itself. Electricity market is divided into four major consumer sectors – residential, commercial, industrial, and transportation. When referring to electricity prices, the combined average price from all these sectors is presented (Figure 24).

Since the beginning of the measuring period in 2001, California electricity prices had been increasing by 6-8 percent annually. Over the 14 years the average price of electricity grew from 8.71 cents per kilowatt hour in January 2001 to 14.54 cents per kilowatt hour in December 2014. If we assume the price per kilowatt hour from 2001 as the base, then by 2014 the price increased by 67 percent. However, these prices represent the average electricity price combined of prices from the four different sectors. Therefore, the percentage increase in some sectors was even greater – 51.1 percent in the transportation sector, 51.8 percent in the commercial sector, 56.8 percent in the residential sector, and 87.5 percent in the industrial sector.



AVERAGE ELECTRICITY PRICES 2001 - 2014

Figure 24: The average price is compiled of prices from four different sectors – residential, commercial, industrial, and transportation. After electricity prices skyrocketed during and shortly after the 2000/2001 California electricity crisis, they continued to grow, although at a lower rate. Source: CEC 2015.

As of now, there are no indicators that the 6-8 percent increase every year will drop before 2020.

Reversely, it might increase as a result of pursuing the RPS, and as a result of the necessary investments into expanding the existing grid (Cook 2013).

There are several drivers to the price increases. Those would be for one the impacts of the environmental regulation policies in California. The second driver – changing climate patterns – can be divided into two main parts. As the results from the previous chapter suggest, the precipitation volumes and patterns within the watershed have a relatively strong influence on the hydroelectricity generation in this area. Since the watershed constantly generates about 50 percent of the state's overall hydroelectricity total, a substantial decrease in electricity generation there means a substantial decrease

in all in-state generated hydroelectricity. Even though the Sacramento River watershed is a prime example of how localized precipitation can be, it can be presumed that if this particular region experiences a significant drawback in rainfall and to it tied hydroelectricity output, then the surrounding regions will most likely experience similar changes in precipitation, and thus similar changes in water availability for hydropower generation. The second aspect is the change in temperature and in extreme temperature occurrences. As mentioned earlier, high elevation powerhouses – which is a majority of those within the watershed – relies on snowmelt runoff. Increased temperature can cause earlier peak runoff and an overall reduction of the snowpack, which in the long run will reduce and deplete water availability in high elevation reservoirs. Beyond this, if the shifted main precipitation season and peak runoff season line over, capacity of smaller scale reservoirs might be exceeded and the excess water will be lost, unless some additional capacity will be constructed. It is also estimated that by the end of the century average household electricity demand may increase by up to 55 percent, partly due to higher cooling demands caused by both increased average temperature and more frequent extreme hot weather events (Auffhammer and Aroonruengsawat 2011). While at the same time the generation from hydropower is decreasing.

To address the second research question – do the production levels from the Sacramento River watershed have a significant impact on the state’s electricity price. As it happened before, in 2000 and 2001 during the electricity crisis, all in-state hydropower very well has the ability to affect electricity prices. During the electricity crisis production from hydro dropped by over 20 percent compared to prior years. However, in this case the reduction in production was rather abrupt and to a larger extent artificially induced by utility companies.

4.5 Summary of the Results

In the power sector, sufficient water supply is not essential to only hydroelectric power plants, but thermoelectric – coal and nuclear fired – power plants as well. The latter two commonly rely on large volumes of river water for cooling. Especially in California the recent hot and from drought plagued years have caused higher river temperatures, which reduced the ability of using the water for cooling. The upon entering the power plant’s cooling process already above average warm water would after releasing back into the stream exceed legal temperature limits (Forster and Lilliestam 2010). This however would not be the biggest problem, as only there is almost no generation from these sources within the Sacramento River watershed.

CHAPTER 5

CONCLUSION & DISCUSSION

The two objectives of this thesis were to determine the effects of changing climate on precipitation, and subsequently hydropower production within California's Sacramento River watershed, and whether those changes have effect on the state's electricity prices. The data used for this study reflect monthly evolution and change in precipitation, temperature, and hydropower production within the Sacramento River Watershed, as well as the evolution of electricity prices within the state of California for the time period between 2001 and 2014.

5.1 Changes in Climate

As discussed in the previous sections, there is abundant evidence that there have been noticeable changes in the climatic conditions within the Sacramento River Watershed. This research area is of great importance to the state as it is the greatest producer of electricity generated from hydropower, and as such it is highly dependent on both precipitation and temperature conditions in the region.

The literature indicates that both precipitation and temperature are undergoing changes on a global scale. Global temperature is expected to rise by 1-2 degrees Celsius by mid-century, but regional changes can be even more drastic depending on various aspects of given area (Duliere, Zhang and Salathe 2009; Luers et al. 2006). California has recorded a temperature increase of 2 degrees Celsius over the past 100 years (Thompson 2015). The temperature data analyses over the 14 year research period have shown that there has been a noticeable increase of temperature within the Sacramento River watershed. On average, the monthly mean value grew more during winter and early spring months

(December – April). The difference in some areas is as large as 2.3 degrees Celsius. Mean temperatures during the summer months remained fairly constant (U.S. Climate Data 2016). The increase for the total area of the watershed, however, is little above 1 degree Celsius. Even though the numeric value itself might not seem as critical, when compared against a 2 degrees increase over a 100 year period, an increase of 1 degree over only 14 years is quite substantial. Rising temperature is of especially great concern when considering that the snowpack of the Sierra Nevada is the second greatest source of water for the watershed. It is expected that the snowpack will reduce by up to 75 percent by midcentury (Mote et al. 2005). Additionally, 2014 showed the lowest recorded snowpack in 500 years (Newbern 2015).

The changes to the precipitation conditions over the Sacramento River Watershed are even more substantial. Analysis of monthly precipitation values between January 2001 and December 2014 has proven that overall rainfall amounts have declined over the entire watershed. However, due to the diverse geography and different climate zones throughout the research area, the extent of the precipitation change is quite localized, as presented in Figure 9. The Sacramento Valley, which is characterized by a Mediterranean climate has recorded only minimal changes in precipitation, with the largest recorded month-to-month precipitation change of 6.9 millimeters. On the other hand, the Sierra Nevada, which is dominated by an Alpine climate, has recorded monthly average changes in precipitation by up to 94 millimeters in certain areas. Decreases in overall rainfall amounts, however, are not the only significant changes that the precipitation pattern is currently experiencing. As noted earlier in this paper, one of the main concerns connected to changing climate is a change in precipitation patterns. Indeed, the monthly rainfall data show a substantial time shift in the occurrence of the main precipitation season (see Table 3). At the beginning of the measuring period in 2001, the watershed received its most precipitation between the months of November and January. Generally, the sum of precipitation for the three months with the most precipitation would total between 1,500 millimeters and 1,900 millimeters. Over the 14 years, the main precipitation season moved forward by up to three months, when the

precipitation-richest months became January, February and March. This, combined with the rising temperature and snowmelt runoff occurring earlier in the year, may cause the two main water supplying events to overlap. Because it is nearly impossible to substantially increase the catchment capacity of reservoirs, some water managers are concerned that the retention capacity of lakes and reservoirs will be exceeded and excess water will be lost (Hunsaker, Whitaker and Bales 2012).

5.2 Changes in Hydropower Generation

Sufficient water supply is crucial for hydropower generation. Thus, any major changes to the water sources in the region will have impacts on the generation of hydroelectricity. In accordance to the results from the previous section, hydropower generation within the Sacramento River watershed has been experiencing changes.

The watershed alone has historically steadily produced about 50 percent of California's hydropower. During dry years, when precipitation was low and the overall in-state hydroelectricity generation was decreasing, the watershed's significance was higher, as it was providing up to 60 percent of the state's hydroelectricity. The decreasing precipitation combined with the reductions in snowpack and water reserves within the watershed are in direct correlation with a decrease in hydropower generation. Over the 14 year research period there has been a substantial decline in hydropower generation. The mean annual generation declined by some 4,000 GWh, from 19,000 GWh per year to 15,000 GWh per year. In late 2005, several extreme precipitation events were recorded, which amounted in close to 2,500 millimeters of precipitation within three months. Because it takes anywhere between three months and two years, depending on the geology and physical geography of the given area, for precipitation to impact the levels of lakes and reservoirs, the precipitation strong-year 2005 was not noticeable in increased hydropower production until later in 2006. For this research area, the data

strongly suggest that the lag between occurring precipitation and the actual increase in hydroelectricity generation is six months. The precipitation rich-year 2005 resulted in 2006 generating record volumes of electricity – over 25,000 GWh was generated only within the watershed. However, ever since then hydropower production has been in a steady decline. By the end of the study period in 2014, the watershed was been producing barely under 10,000 GWh.

Historically, hydropower has played an important role in California's electricity mix. For decades it has been the largest renewable energy producer in the state. But even this role is vanishing. There are several reasons. As noted above, the overall mean annual amount of hydroelectricity production has decreased by over 20 percent within the 14 years research period, and has been in steady decline since 2006. On the other hand, electricity demand and consumption have been steadily growing over the entire research period (see Figure 12). Hydropower could not cover the growing demand, which resulted in increased production from other sources as well as increased electricity imports from the northwest and the southwest (see Figure 16). This is one reason for the percentage drop of hydropower in California's electricity mix. Other reason is the introduction of new sources of electricity – particularly wind and solar power. This is also the reason for hydroelectricity's decreased contribution to the renewable energy sector. In 2001, when hydropower from the Sacramento River Watershed was supplying around 13,000 GWh, wind and solar energy were generating barely over 5,000 GWh statewide. However, the capacity of wind energy has been increasing almost linearly over the entire period (see Figure 20). By 2014 wind energy alone was generating almost 13,000 GWh annually. In fact, in 2014 more electricity has been generated from wind power than from hydropower for the first time in California's history. Electricity generation from solar energy had been low until 2011, when the sector boomed and started growing exponentially. While in 2011 solar energy produced 1,097 GWh – for the first time passed the 1,000 GWh mark – in 2013 it was already over 4,000 GWh and over 10,000 GWh by

2014. Thus, today wind and solar energy together generate over 2.5 times more electricity than hydropower. It can be expected that the trend in both solar and wind energy generation will continue, which will result in further decreases in the proportion of hydropower-generated electricity among renewable energy sources.

5.3 Electricity Prices

Electricity prices have been growing for decades, at both the national and the state level. According to the EIA, electricity prices have increased by 85 percent over the past 25 years (EIA 2009). A major increase in California's electricity prices happened during the 2000/2001 electricity crisis. Within few months prices went up by up to 30 percent. The 14 year research period is no exception to this trend. California uses four pricing sectors with different rates for its end-users. These are: residential, commercial, industrial, and transportation. All sectors have experienced increases in prices, some more substantial than others. Electricity rates have been the highest in the residential sector, with 10.89 cents per kilowatthour in January 2001. By the end of the study period in December 2014, the price per kilowatthour in the residential sector was 17.08 cents, which corresponds to a total increase of 57 percent over the study period. The prices within the commercial sector started at 9.28 cents per kilowatthour and went up to 14.09 cents per kilowatthour, which results in a total increase of 52 percent. Analysis for electricity rates in the transportation sector could not be started with the year 2001, as there were virtually no electric vehicles, thus there was no market. Transportation as a separate electricity end-use sector was first introduced in January 2003. In accordance to the emission control policies, the electricity rates were the lowest among all other rates, in order to encourage and support the electric vehicles market. The rates started at 5.62 cents per kilowatthour in January 2003, and continued to grow to 8.49 cents in December 2014. This corresponds to the lowest increase in rates among the four sectors

– 51 percent. In 2001 the industrial sector had fairly low rates – 5.75 cents per kilowatthour. However, it was the industrial sector that experienced the steepest increase in rates. By 2014 the electricity prices grew by 87 percent, to 10.78 cents per kilowatthour.

Initially, California was generating 19 percent of its electricity from hydropower. The Sacramento River Watershed was producing around 51 percent of the state’s hydroelectricity. The overall production increased by almost one half – in 2014 hydropower was providing less than ten percent of the state’s electricity. Under these conditions, the significance of the watershed has actually increased. While at the beginning of the analysis period the Sacramento River Watershed was providing slightly over 50 percent of all instate hydroelectricity, in 2014 it was close to 60 percent. This illustrates how, even though the entire state suffers from decreasing hydropower, in the Sacramento River Watershed the decrease is slower. Over the 14 years study period, there have been quite significant variances in both precipitation and hydro-electric production, which was directly affected by precipitation. Despite the size of the watershed, its electricity production volume, and the variability in electricity production, we have found no evidence of a relationship between electricity production and the movement of electricity prices at the state level.

This study analyzes the effects of climate change only within one particular geographical area. The area is very unique due to its varying climatic conditions despite its relatively small size, as well as due to its hydrologic conditions and its importance in California’s electricity market. Even though the results are not perfectly applicable in other parts of California, or the United States for that matter, they show the general direction where hydropower is headed, and more generally the interplay between various forms of renewable power.

However, this study has several caveats. First and foremost, it views water strictly as a fuel source for hydroelectricity generation. The value of water as provider of riverine habitats in the

Sacramento River Watershed remains unnoted, as well its value for industrial and irrigation purposes.

There are several policies to maintain minimal flows in the rivers beneath the electricity generating dams. Water managers will likely have to decide which purpose is more crucial for the water, if the climatic patterns keep following their current trends (Wagner et al. 2011; Kimley, Cech and Thompson 2007).

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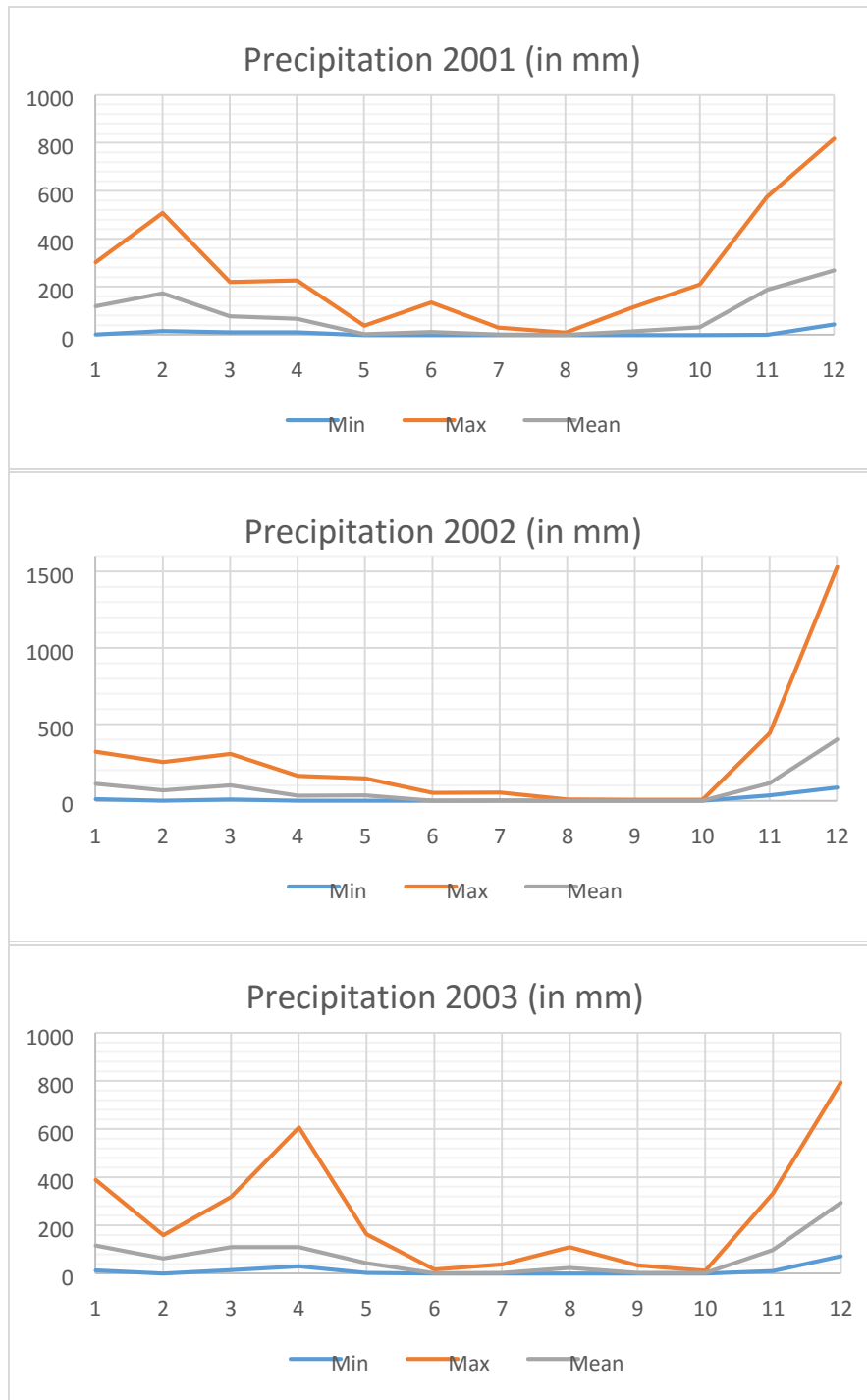
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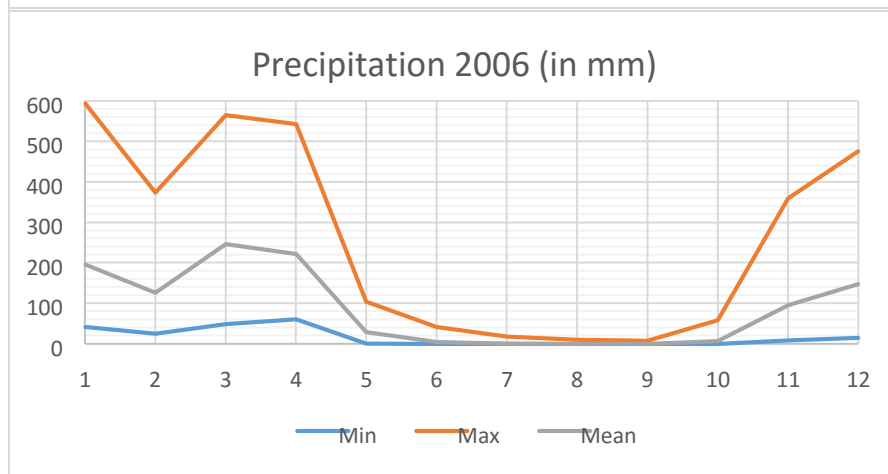
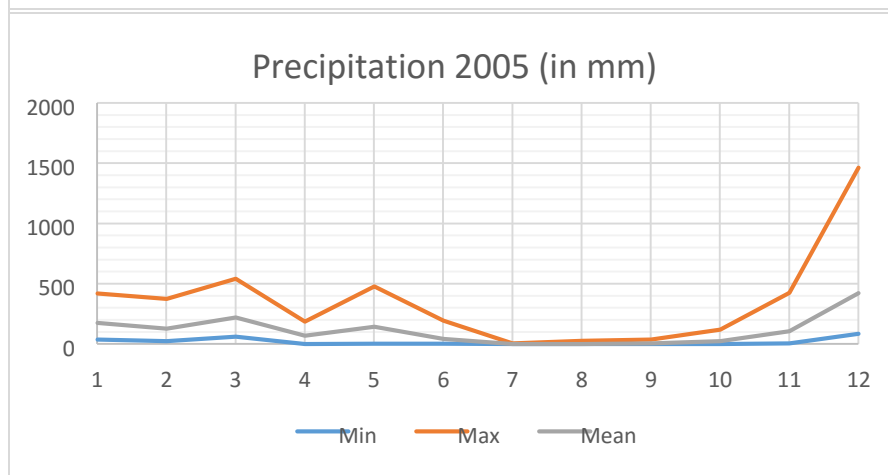
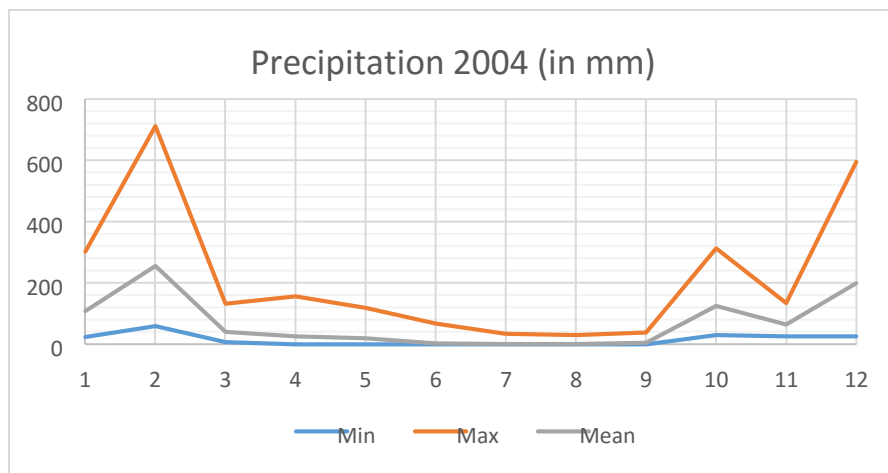
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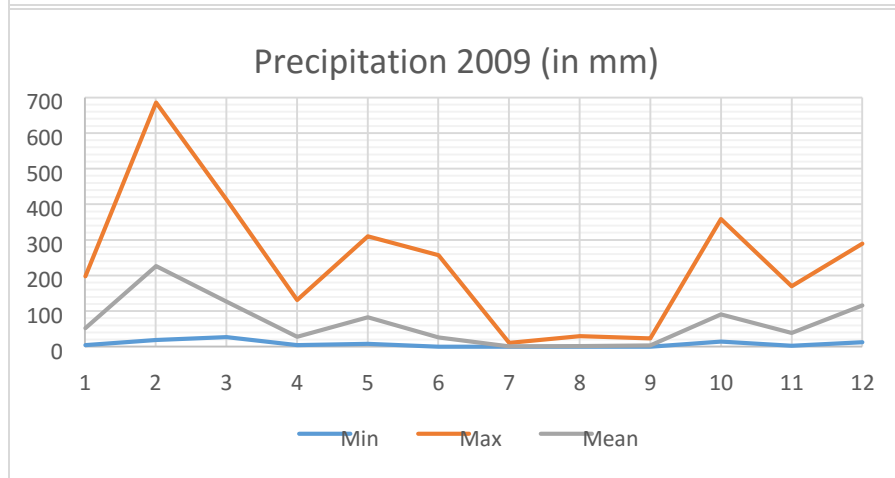
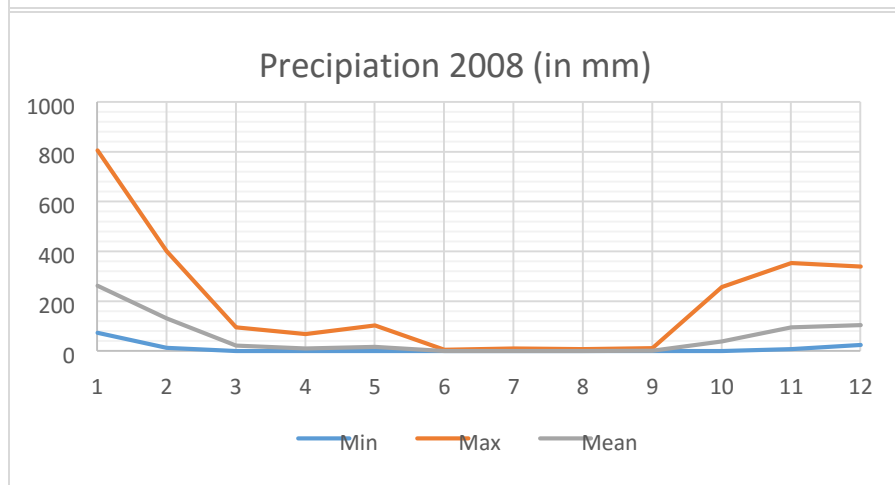
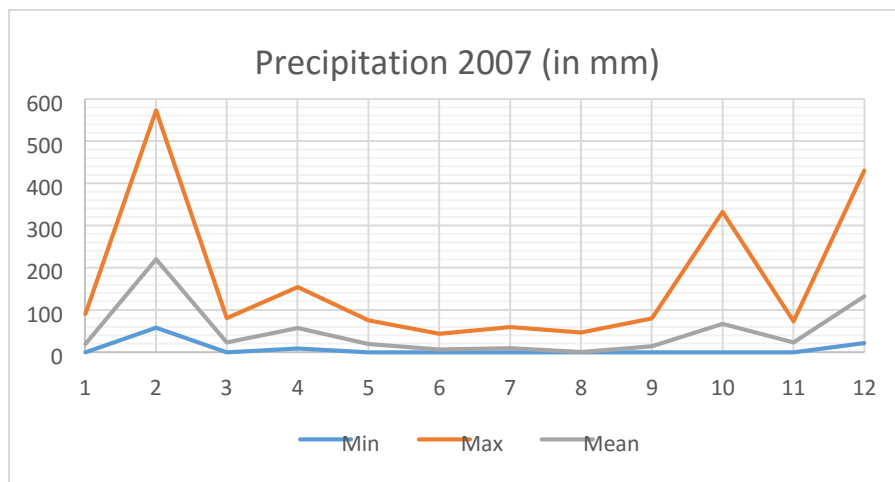
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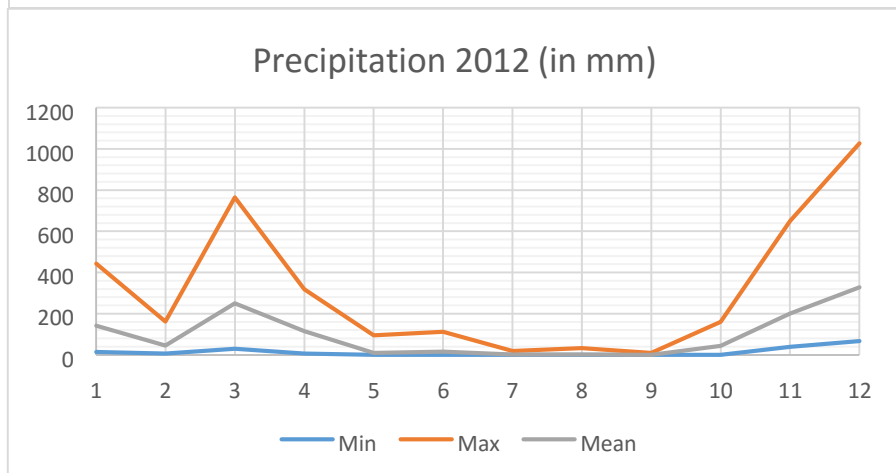
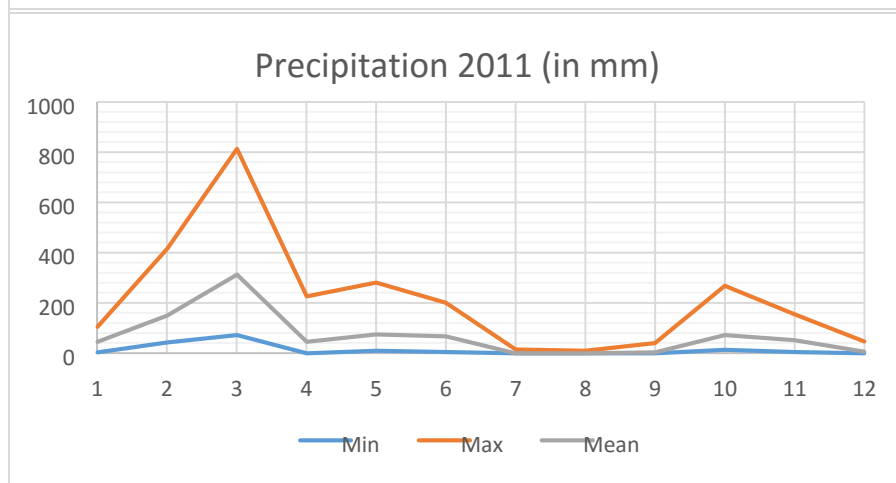
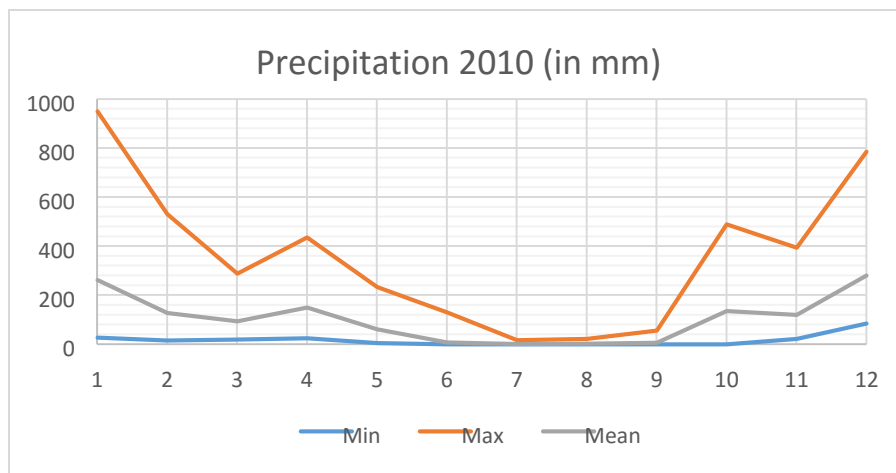
APPENDICES

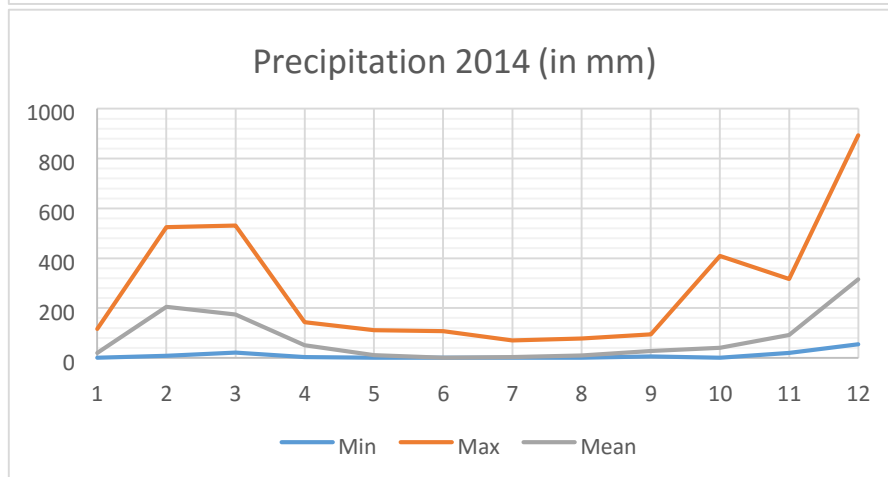
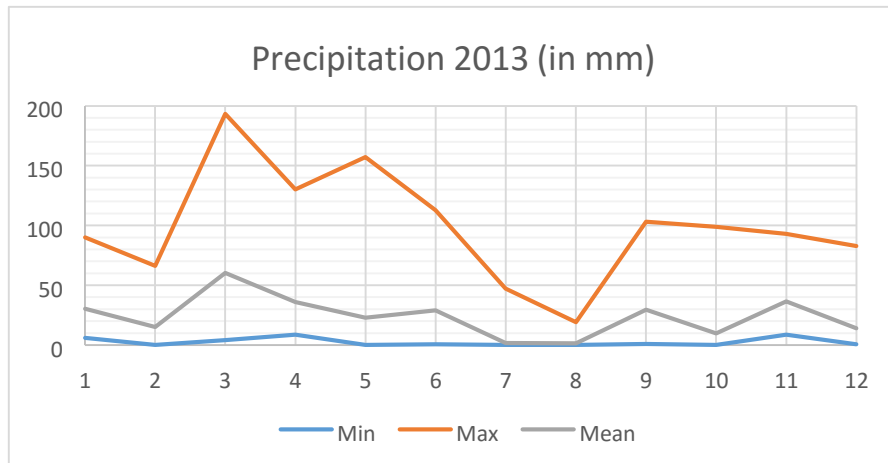
Graphs of monthly average, minimum and maximum precipitation in millimeters for each month between January 2001 and December 2014.











VITA

Graduate School
Southern Illinois University

Daniel Fucik

daniel.fucik@yahoo.com

Charles University Prague
Bachelor of Arts, International Relations, September 2012

University of Regensburg
Bachelor of Arts, International Relations, September 2012

Thesis Title:

Effects of the Changing Climate on Hydropower Production in the Sacramento River
Watershed and California's Electricity Prices

Major Professor: Silvia Secchi