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Water Withdrawal and Consumption Reduction Analysis for Electrical Energy Generation System

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WATER WITHDRAWAL AND CONSUMPTION REDUCTION ANALYSIS FOR ELECTRICAL ENERGY GENERATION SYSTEM

by

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ABSTRACT

WATER WITHDRAWAL AND CONSUMPTION REDUCTION ANALYSIS FOR ELECTRICAL ENERGY GENERATION SYSTEM

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The University of Wisconsin-Milwaukee, 2015
Under the Supervision of Professor Hamid Seifoddini
Under the Supervision of Co-Advisor Professor Adel Nasiri

There is an increasing concern over shrinking water resources. Water use in the energy sector primarily occurs in electricity generation. Anticipating scarcer supplies, the value of water is undoubtedly on the rise and design, implementation, and utilization of water saving mechanisms in energy generation systems are becoming inevitable. Most power plants generate power by boiling water to produce steam to spin electricity-generating turbines. Large quantities of water are often used to cool the steam in these plants. As a consequence, most fossil-based power plants in addition to consuming water, impact the water resources by raising the temperature of water withdrawn for cooling.

A comprehensive study is conducted in this thesis to analyze and quantify water withdrawals and consumption of various electricity generation sources such as coal, natural gas, renewable sources, etc. Electricity generation for the state of California is studied and presented as California is facing a serious drought problem affecting more than 30 million people. Integrated planning for the interleaved energy and water sectors is essential for both water and energy savings.

A linear model is developed to minimize the water consumption while considering several limitations and restrictions. California has planned to shut down some of its hydro and nuclear plants due to environmental concerns. Studies have been performed for various electricity generation and water saving scenarios including no-hydro and no-nuclear plant and the results are presented. Modifications to proposed different scenarios have been applied and discussed to meet the practical and reliability constraints.

To

My Beloved Family,

And My Amazing Husband

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LIST OF ABBREVIATIONS

EIA: Energy Information Administration

CEC: California Energy Commission

DOE: Department Of Energy

PV: Photovoltaic

ESS: Energy Storage Systems

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CHAPTER 1

1- Introduction

Traditionally water and energy have been addressed to be as two separate issues. However they are deeply interdependent and a successful management requires consideration of both. The most important reason behind this mutual dependency is that producing energy requires a large share of available water starting from the extraction of the fuel and constructing the power plant to the cooling process in the electricity generating phase. On the other hand collecting, treating, transferring and storing water consumes a large amount of energy [1].

This prominent inter-relationship between water and energy has been acknowledged in the United States for a long time, but recently it has been widely investigated especially by Department Of Energy or DOE since limited water sources are making the energy sector vulnerable. There has been a lot of reports released by DOE in the past five years providing data and analysis, challenges and opportunities, productive synergies in water-energy nexus and some strategies to increase the efficiency of water usage in electricity generation and vice versa.

Although water is an abundant resource, the wise utilization of this precious source has always been considered in developed countries including US since, water is not always available in the place and time needed.

Based on drought statistics 2015 was California's fourth consecutive dry year and it has been forecasted that 2016 will be even drier. To reduce the effects of this severe drought, California took some actions in order to reduce water consumption in all the sectors so far and have been through a lot of transformations. They started water saving regulations in 2012 and added a lot of restricted laws and limitations in water consumption for various sectors since then.

The energy sector has the second place after agriculture in consuming water with 14 percent share of total water consumed in US. Therefore a comprehensive management of water-usage in this sector can save billions of gallons of water in California.

The US Energy Information Administration and the California Energy Commission are two major organizations, which provide detailed information in categories related to the energy sector in their monthly or daily reports. EIA collects the information for the entire US while CEC presents the data for the California area. A big share of data used in this study comes from these two associations.

This report provides

1) Overviews the nexus between water and energy sectors.
2) Offers some strategies while considering some limitations and restrictions that are growing rapidly in both of these areas.
3) Reviews water consumption in the energy sector specifically, all different types of electricity generating technologies such as coal, natural gas, hydro, wind and etc.
4) Discusses various cooling systems
5) Identifies different parts of the process in producing electricity that need water from extracting the fuel and washing the equipment to drive the turbines
6) Compares different technologies in case of water consumption and withdrawals.
7) Deliberate different energy generation mixes and scenarios for California considering all their pros and cons.
8) Discusses the results for each scenario and suggests some strategies to complement them.

Chapter 2 reviews the inter-dependency between water and energy, their relationship and some of the factors affecting this relation following with a short discussion on how to control these factors.

Chapter 3 complements this information with adding different energy generation technologies, different methods of producing electricity using each source of energy and their associated cooling systems. Water consumption and withdrawal of each method is also presented using different references and reports derived from major organizations in this area.

Chapter 4 brings the report one step forward with presenting a linear model that uses the data from chapter 3 to minimize the amount of water consumed in the energy sector with choosing the least water dependent technologies.

Chapter 5 investigates different scenarios in energy generation mixes including no-hydro and no-nuclear plants, identifies water consumption for each scenario and finally offers some strategies to cover the disadvantages of each plan for California.

CHAPTER 2

2- Literature Review

2-1 Water for energy: Energy is one of the biggest water-intense sectors. With 14 percent share of total water consumption in US, ranks in the second place after agriculture. Recent drought emergency throughout the entire US especially in 2012 was an alarm for the power sector of vulnerability of this sector to water shortage.

Water use in the energy sector primarily occurs in two areas: fuel production and electricity generation. Fuel production such as coal mining, natural gas extraction, and growing crops for biofuels requires drastic water supplies, as well as purifying fuels and transportation of them. Most power plants generate power by boiling water to produce steam that spins electricity-generating turbines. Massive quantities of water are often used to cool the steam. Using water in generating energy raise water temperature that can harm aquatic organisms as well as posing water quantity problems. [2]

Power plants that are built in areas with limited water resources, threaten the quality and availability of freshwater for other essential needs. The energy-water connection can turn into a problem with dangerous consequences for both sectors where the water is scarcer. So taking some actions to reduce this dependency is necessarily needed.

The water intensity for different technologies is different. For example the water consumed by renewable sources of energy like wind and solar PV is negligible, but even these technologies need water at very basic levels such as building the turbines and solar panels.

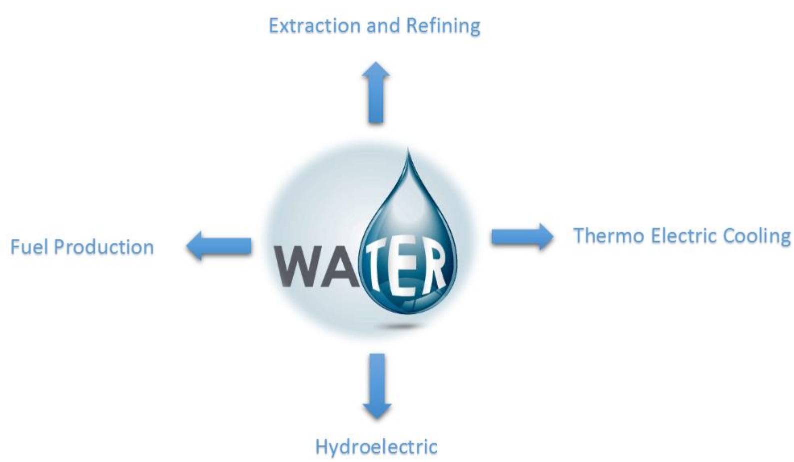

Figure 1 Water for Energy.

2-2 Energy for water: Energy is used in five stages in the water cycle including Extracting and conveying water, treating water, Distributing water, Using water and Collecting and treating wastewater.

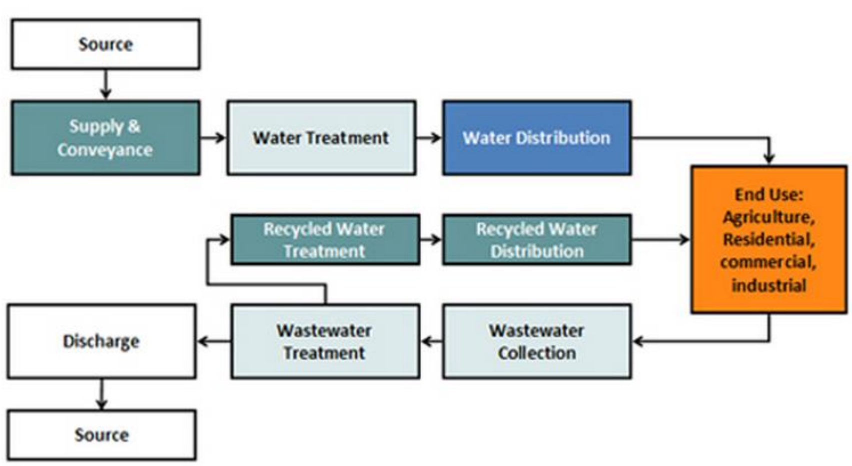

Figure 2 different water related actions that use energy in their process *[3]*.

Energy intensity is described as the amount of energy consumed per unit of water to perform all the processes related to water management such as groundwater extraction, pumping, pressurizing, desalting and treatment and it should be expressed by the number of kilowatt-hours consumed per million gallons (kWh/MG) [3].

According to US Environmental Protection Agency, drinking water and wastewater systems account for approximately 3-4 percent of energy use in the United States, equivalent to approximately 56 billion kilowatts (kW), or $4 billion, is used in providing drinking water and wastewater services each year. Adding over 45 million tons of greenhouse gases annually. Furthermore, drinking water and wastewater plants are typically the largest energy consumers of municipal governments, accounting for 30-40 percent of total energy consumed. If water and wastewater utilities could reduce energy use by just 10 percent, it would save about $400 million annually [4].

2-3 Water withdrawal and consumption:

The amount of water used by the energy sector can have two forms with two different definitions: water withdrawal and water consumption. In The Handbook of Water Use and Conservation, by Amy Vickers, water withdrawal is defined as "water diverted or withdrawn from a surface water or groundwater source." Water consumption, on the other hand, is defined as "water use that permanently withdraws water from its source; water that is no longer available because it has evaporated, been transpired by plants, incorporated into products or crops, consumed by people or livestock, or otherwise removed from the immediate water environment. Water withdrawal measures the ratio of dependency of that

process to water resources, while water consumption can evaluate the impacts of water scarcity on that sector.

2-4 Water-Energy dependency factors:

There are several factors that can have effect on water-energy nexus. Some of them are as follow:

- ✓ **Climate change:** including change in precipitation patterns and temperature. For example rising temperature can have effect in both electricity generation and water availability by reducing the efficiency of thermoelectric generation and increasing the demand for electricity.
- ✓ **Population growth and migration patterns:** rising population can lead to more demand for both electricity and water so it will be hard to manage both of them in order to satisfy the demand.
- ✓ **Technology options:** although there are a lot of options for generating electricity but considering water-energy nexus, options would be limited to those that have less water intensity. Most of the renewable energies' power plants such as wind and solar PV power plants don't need water in their process of generating energy but still water might be required in the first steps of producing turbine or solar panel in a very negligible amount. The amount of cooling required by any steam-cycle power plant is determined by its thermal efficiency. Some of the technologies might withdraw a

Figure 3 Different energy generation technology options.

tremendous amount of water while only a small percentage is evaporated.

- ✓ **Location of power plants:** one of the most important decisions that can affect the amount of water used by a power plant is the location of the power plant. This decision of course should consider all the factors mentioned above. Water rights and energy policies vary in different states of United State as well as many other nations. [5]

The consequence of this strong interconnection between energy and water is that problems for one can create problems for the other. The continuous increase of the world-wide demand for water and energy makes it crucial to make their use more efficient. So, we need to make smarter choices to help save both energy and water.

But, making a wise decision is not simple. First, we need to investigate all the feasible solutions and after that we can decide which one is the best in case of cost or availability in that certain area.

Of the all four factors that have an effect on the annual amount of water used in energy sectors, climate change and population growth are the hardest to manage, if any control on these were possible, it would take a long time for California to implement it. Moreover, the location of power plants cannot have great impacts on the final results since this study is investigating all the power plants within California's borders. Therefore, technology options for electricity generation is the only factor left to be discussed.

There are a lot of actions that can be done in the energy sector to reduce the amount of water consumption and withdrawals:

1) Using less electricity or transportation fuel by making appliances, buildings, and vehicles more efficient
2) Using renewable energy technologies such as wind and photovoltaics to reduce the amount of water needed for producing energy
3) Retrofitting old coal or nuclear plants with more water-efficient cooling technologies could increase water consumption, potentially even doubling it, but could reduce water withdrawals by two orders of magnitude.

All these strategies need a lot of detailed plan of actions and complementing modifications to help achieving the final goal. This study goes over some of the solutions in a detailed level and examines the results applicability in the real world.

2-5 Why California:

Between all 50 United States, California is facing a serious water shortage. According to a report by Jeffery Bell at March 2014 “Last year was the state’s driest since the start of record-keeping in 1895, and this year is likely to be even drier”. There is also another report by California energy commission that says California’s population has more than tripled in the past 50 years and is expected to nearly double again in the next 50 [6]. More population means more demand for water.

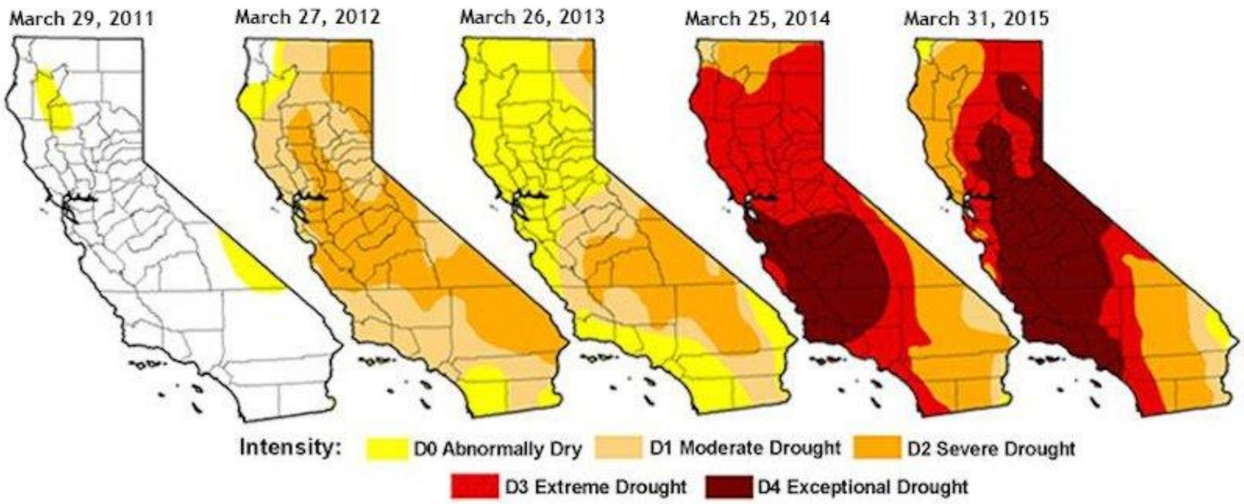

Figure 4 California drought from 2011 to 2015 *[55]*.

Here is a quick look on California's drought statistics according to national drought mitigation center. As a result integrated planning between energy and water sectors in California is essential.

Water availability is not the same all over through California. Two thirds of California's water happens to be in the northern parts of the California while two thirds of state's population is located in southern parts, consequently there is a complexity in the water distribution system. State water project uses 12.2 billion kWh annually to transfer water to southern California and this average will increase as the population growth occurs in California. [7]

2-6 Water intensity for energy generations in California:

Water intensity for electricity generation strongly depends on three factors:

Energy source: The amount of water required for energy generation is highly dependent on the type of the power plant. For example a hydroelectric power plant needs

water in the whole process, a coal power plant uses water in mining the coal as well as it's cooling systems and finally there are some power plants that don't need water in the main process but still they need water for some minor processes, for example a wind turbine needs to be washed to work properly. A washed wind turbine can work much more efficient than a turbine that has a heavy dust on it.

Conversion technology: The conversion technologies that a plant is using can definitely have impact on the amount of water that is needed to produce energy. A group project in Santa Barbara University used a very good instance to explain it. According to the report "A natural gas plant using combined cycle technologies captures more of natural gas's latent energy than a single cycle plant, decreasing the water required per unit of energy"

Cooling technologies: Finally the greatest impact on the water intensity in energy generation is related to the cooling technology that is applied by the power plant. Cooling is the largest water intensive process in most of non-renewable power plants. A 500 MW power plant using once-through cooling withdraws over 45,420 cubic meters of water per hour with only a small amount going to non-cooling process requirements.

2-7 Different types of cooling technologies:

Most of the power plants that use a turbine to generate electricity need to boil water to generate steam and then use the steam to spin the turbine. Once steam has passed through the turbine, it must be cooled back before it can be reused to produce more electricity. There are multiple types of cooling technologies to condense steam and each power plant can use any of them depending on the energy source or the location of the power plant. There is no

certain type of technology that is optimal for all power plants in all locations. Some withdraw more water but consume less and some others withdraw less but consume most of it. Moreover there is a big difference between capital costs for applying either of these technologies. [8], [9]

2-7-1 Once-through cooling systems:

Water is withdrawn from a natural water source, goes through a steam condenser and then pumps back into the boiler, slightly heated usually about 10 to 30ºF [10] and then comes back to the source again. There is no water consumed in the cooling process but the water evaporates when it comes back to its reservoir because of the high temperature and it usually will replace with rain water. Withdrawal rates are typically in range of 500 GMP per MWh. It is hard to calculate the amount of water that is evaporated from the body but it is estimated to be 0.5–2% of the withdrawn amount, the amount of water evaporated is highly dependent to the type of the power plant and the temperature of the returned water. This type of cooling was traditionally very popular due to its simplicity and low cost but, it has been less popular with scarcity of water sources.

2-7-2 Recirculating Cooling Systems:

Recirculating systems known as wet cooling towers withdraw less water from the source compare to once through cooling (about 2-3%). This is what makes recirculating a better choice for environment. By withdrawing less water and using that water for several times it prevents from pouring high temperature water back into the reservoir that can kill a lot of marine creatures and change their habitat. The cooling process is same as once through cooling but the difference is the temperature is higher and the water will be pumped

to a cooling tower to be cooled instead of going back to the source. The water that is evaporated in this stage will be the water consumption and the rest of the cooled water recirculate to the process with the water added to make up the evaporation.

In case of efficiency wet cooling towers are in the second position after once through cooling but installing the equipment's are more expensive than once through systems, still not as expensive as dry cooling technology.

2-7-3 Dry cooling systems:

There are two types of dry cooling technologies, direct and indirect cooling. In direct dry cooling steam is being transferred to an air cooled condenser, it will be cooled and pumped again to the steam condenser. In indirect dry cooling as it is clear of the name there is an intermediate process. Heated steam will transfer to a water cooled condensers and the water itself will be cooled in an air cooled condenser. The efficiency of dry cooling is less than wet cooling and that's because the heat capacity of air is less than water, so the temperature of steam after being cooled in air dry cooling is always higher than any type of cooling that water is involved in the cooling process. In case of cost a 500MWh natural gas combined cycle power plant with dry cooling technology costs about 8-27 million dollar, about 5-15% cost of total power plant, more than the same plant with recirculating technology.

2-7-4 Hybrid cooling system:

Hybrid cooling systems are dual cooling systems with both wet and dry cooling components, so a hybrid system can have combined benefits. In hot days of summer hybrid cooling can use more wet cooling components to increase the efficiency compare to dry

cooling and in other times of the year it can use more dry cooling components to reduce the amount of water needed in the process.

About 43 percent of thermoelectric generators in the United States use once-through cooling and 53 percent use wet-recirculating while this percentage for dry-cooling is so small. Only 56 operable cooling system in United States is using dry cooling and 5 out of 1655 total cooling systems are hybrid. [10], [8], [6]. Table below sums up all the information about the water intensity for different cooling technologies.

Table 1 Water intensity of different cooling technologies, gallons per MWh *[7]*, *[9]*.

Cooling technology	Average Water Consumption	Average Water Withdrawal	Efficiency Highest to Lowest	Cost Lowest to Highest
Once-through	0.38	142.69	1	1
Wet-Recirculating	4.16	4.54	2	2
Dry	Less than 5% of wet cooling	Less than 5% of wet cooling	4	3
Hybrid	Variable between wet and dry	Variable between wet and dry	3	4

2-8 Operation Research

There are many different definitions of OR. “OR is a scientific method of providing executive departments with a quantitative basis for decisions regarding the operations under their control”, Morse and Kimbel (1946). “OR is a scientific approach to problem solving for executive management”, Kitee. Different phases of OR are as follow [11]. Operations Research (O.R.) is a discipline that deals with the application of advanced analytical methods to help make better decisions [12] and that is why this study uses operation research linear programming

technique to formulate the model. There are different phases in formulating a model with operation research.

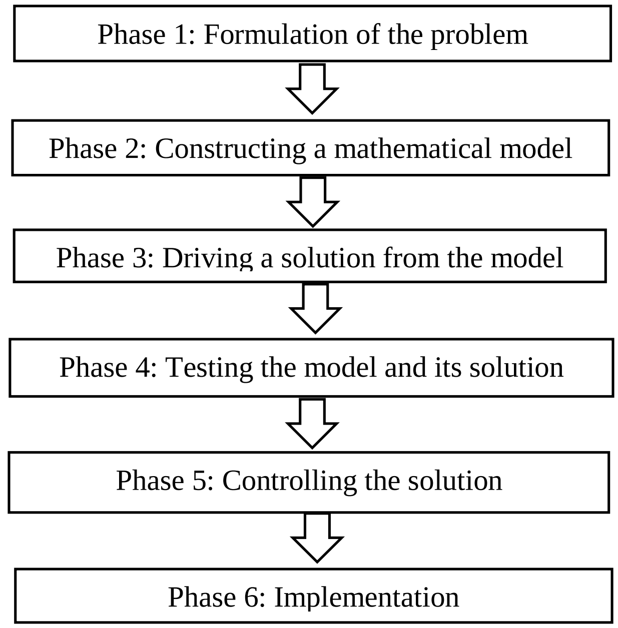

Figure 5: Operation Research phases *[11]*

2-8-1 Formulation of Problem

To find the solution of an OR model, problem should be formulated in an appropriate model. The following information are needed for problem formulation [11].

1) Decision Makers
2) Objective Function
3) Controllable Variables
4) Uncontrollable Variables
5) Restrictions and Constraints

2-8-2 Constructing a mathematical model

In this phase, model should be reformulated in an appropriate model to be more convenient for further analysis. A mathematical model should be able to represent the system under study in all aspects. A mathematical model consists of objective function, decision variables and constraints.

2-8-3 Driving a solution from the model

By using OR techniques and methods, a solution for the mathematical model should be found. In OR models, it’s always desirable to find the optimal solution. Optimal solution in the one that maximize or minimize the objective function.

2-8-4 Testing the model and its solution

After getting the solution, it is necessary to test the solution for errors if there is any. This may done by re-examining the formulation of the problem and comparing it with the original model which help to reveal any mistake.

2-8-5 Controlling the solution

The model requires immediate modification as soon as one or more of the variables change. As the conditions are constantly changing in the real world, the model and optimal solution may not remain valid for long time and should be updated continuously.

2-8-6 Implementation

It’s the final phase of each OR model. As change occurs, the model and solution should be updated immediately.

2-9 Linear Programming

Linear Programming is one of operation research techniques that can best fit with the problem of this study. The term Linear Programming (LP) is the combination of the two terms. “Linear” means that all the relations in the problem are linear and “Programming” refers to the process determining particular program. The linear programming method is a technique of choosing the best alternative from the set of feasible alternatives while objective functions and constraints can be expressed as linear mathematical function.

The linear function that is going to be optimized is the objective function and the conditions of the problems are constraints. Linear programming is a widely used in field of optimization since many practical problems in operations research can be expressed as linear programming problems. A general linear problem can be stated as follows [11]:

Find X1, X2, …Xn which optimize the linear function.

Z= C1X1 + C2X2 + ……… + CnXn

Subject to the constraints:

A11X1 + A12X2 + ……. + A1nXn (< = >) b1

A21X1 + A22X2 + ……. + A2nXn (< = >) b2

………………………………….

Am1X1 + Am2X2 + ……. + AmnXn (< = >) bn

Xj > 0 , j=1,2,3,…..,n

The problem of solving a system of linear inequalities dates back at least as far as Fourier, who in 1827 published a method for solving them [13]. The first linear programming formulation of a problem that is equivalent to the general linear programming problem was given by Leonid Kantorovich in 1939, who also proposed a method for solving it. He developed it during World War II as a way to plan expenditures and returns so as to reduce costs to the army and increase losses incurred by the enemy [14].

The main advantages of linear programming are as follows [11]:

- It indicates how the available resources can be used in the best way to optimize the objective function.
- It helps in attaining the optimum use of the productive resources and manpower.
- It improves the quality of decisions.
- It also reflects the drawbacks of the production process.
- It helps in re-evaluation of a basic plan with changing conditions.

CHAPTER 3

3- Energy generation technologies

There are two types of energy fuels, renewable and nonrenewable energies. This section briefly explains different energy sources and their related power plants cooling technologies and water intensity. The California Energy Commission is an organization that reports a lot of energy related databases each year. The most recent report about energy generation mix is showing that natural gas has the largest portion in providing electricity for the California State.

Table 2 Total in-state electricity generation in California for 2014 *[15]*.

Fuel Type	California In State Generation (GWh)	Percent Of California In State Generation
Natural Gas	121,934	61.3%
Nuclear	17,027	8.6%
Large Hydro	14,052	7.1%
Wind	12,997	6.5%
Geothermal	12,186	6.1%
Solar	10,557	5.3%
Biomass	6,721	3.4%
Small Hydro	2,426	1.2%

Coal	1,011	0.5%
Oil	46	0.02%
Others	16	0.01%
Total	198,973	100%

There was a large change in the percentage of renewable sources in the recent years. California experienced its driest year ever in 2014. Below normal precipitation rate made California shut down its hydro facilities in 2014. Although natural gas usually compensate for the shortage in dry no-hydro years, After January 2014 an increase in wind and solar generation made up for 32 percent drop in hydro. 1000 percent more generation from 2010 to 2014 made solar rank as the fastest growing technology among all other technologies and wind facilities in California increased their generation by 2.4% [16].

3-1 Natural Gas:

Currently there are 422 natural gas fired power plants in California [17]. After governor's statement regarding drought emergency in January 2014, California had to shut down some of its hydroelectric power plants because of the drought and natural gas picked up the shortage by either opening new power plants or increasing their efficiency and capacity by changing some technologies. According to federal data natural gas is now supplying more than 61% of the state's power but 90% of it, is imported from the Southwest, Rocky Mountains, and Canada through pipelines.

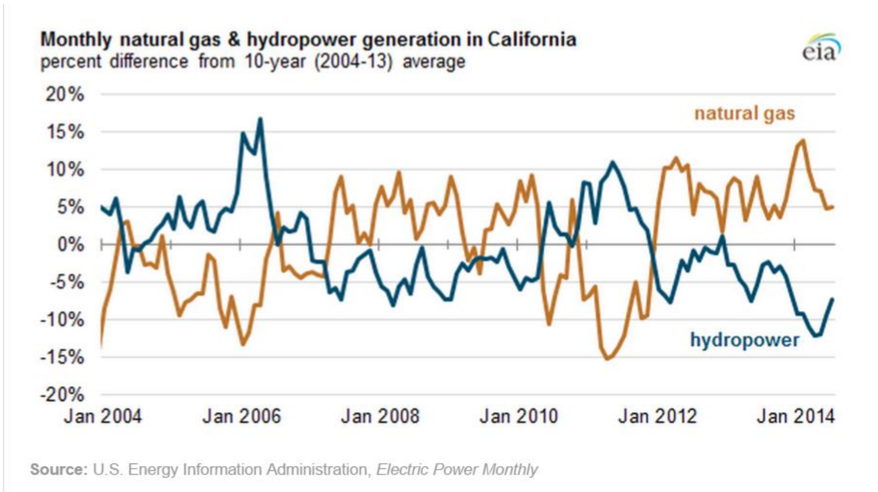

Figure 6 Electric power monthly *[56]*.

There are different types of technologies that have been used in natural gas power plants. The oldest method is by using the combustion of the gas to heat the water and convert it to steam and then use the steam to drive a turbine. But there are newer methods that almost double the efficiency of this process. In the new method that is called combined-cycle technology, combustion of the gas drives the turbine and the result of this process is the heated (about 900 $^{\circ}$F) gas. Now by transferring the heat to the water and convert it to steam they can use the steam to drive a second turbine.

Combined cycle technology can increase the efficiency from 30% to 60%. There is also a technology called single-cycle that is basically the first process of the combined-cycle technology and there are not that many power plants that are currently using it. But its advantage is that it is the cheapest technology in case of capital cost. [7]

The thermal efficiency of California's gas-fired generation improved more than 22 percent between 2001 and 2012 because of an increased reliance upon combined cycle power plants (US Energy Information Administration).

Natural gas power plants all over California are using all three methods of cooling. Most of the new power plants are decreasing their water use by applying dry or hybrid cooling technologies.

Table 3 Water withdrawal and consumption of natural gas in gallons per megawatt-hour [18], [9].

Generation technology	Natural gas steam turbine	Natural gas steam turbine	Natural gas combined cycle	Natural gas combined cycle
Cooling technology	**Withdrawal**	**consumption**	**withdrawal**	**consumption**
Once through	10000-60000	95-291	7500-20000	20-100
Wet-Recirculating	950-1460	662-1170	150-283	130-300
Dry cooling	0-4	0-4	0-4	0-4

Extracting, refining and transportation of oil and naturals gas are other sources of water consumption but the amount of water required is negligible compare to cooling process. There are also different types of technologies for extracting oil and natural gas. The amount of water required is dependent to the type of technology used.

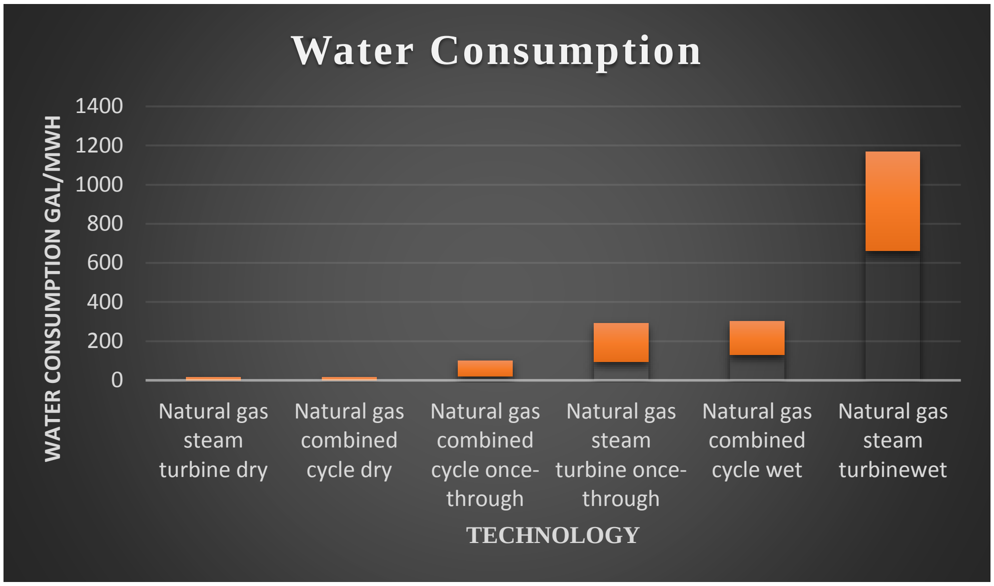

Figure 8 Water consumption of natural gas technologies.

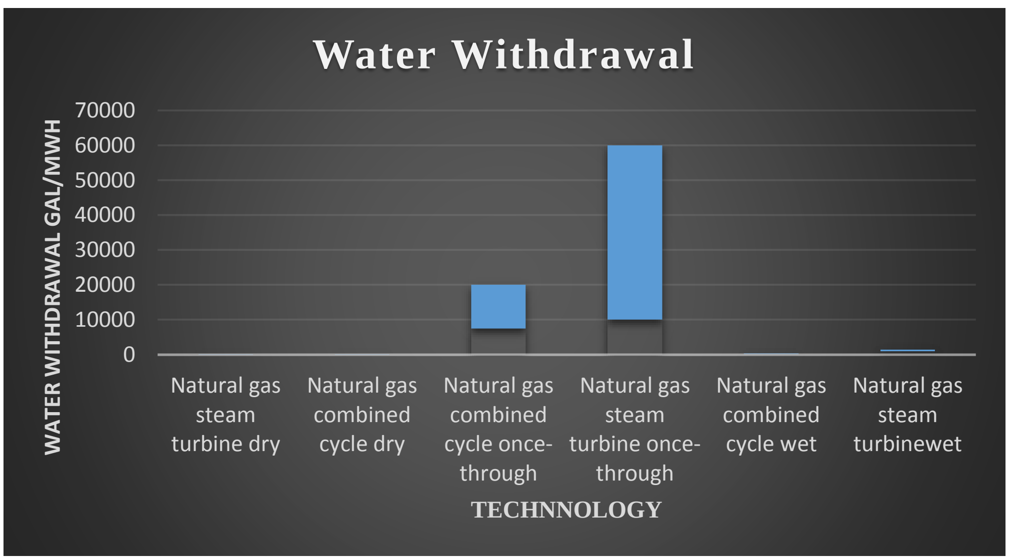

Figure 7 Water withdrawal of natural gas technologies.

3-2 Hydroelectric:

Currently there are a total of 365 operable hydroelectric power plants in California which are fulfilling about 8.3% of California's electricity demand according to a 2015 report by California energy commission.

Dams and run-of-river are two common types of hydro facilities in California. Also hydro power plants are called small hydro or large hydro depending on their capacity compared with 30 MW. In dam facilities water is elevated to a height and then released over a turbine to produce the amount of pressure needed while run-of-river facilities divert the flow of river toward a turbine and then return it back to the stream.

There is another type of hydro facilities that is useful for the problem of peak demand. Pumped storage works with storing water in a higher level reservoir in off peak hours and use it in peak hours, but there is a need for building a big space in a high altitude to reserve the water that is very cost intensive. Although the amount of electricity generated by this method is less than the electricity needed to pump the water to the reservoir, but it is economical because there is a big difference between the cost of electricity during off peak and peak demands [19].

Figure 9 Run of river *[50]* Dam *[51]* Pumped storage *[52]*.

Hydroelectric generation is the most intensive renewable source in case of water. But unlike nonrenewable power plants a hydro power plant doesn't need water for cooling process. Water is actually the basis of the process and the electricity generated is highly dependent to the time of the year and precipitation rate.

There are also several factors affecting the amount of water consumed by a hydroelectric power plant. Higher ratio of reservoir surface area to hydraulic head results in high rates of evaporation relative to the energy generated. Therefore facilities with a large hydraulic head, consume less water while generating more energy. Additional factors affecting rates of evaporation include reservoir location and size, local topography, dam type, and climate.

According to California's RPS large hydroelectric power plants doesn't count as renewable sources of energy so the potential for opening large hydroelectric power plants is extremely limited. Also, there are a lot of environmental consequences that they are trying to avoid.

Table 4 Water withdrawal and consumption of hydro in gallons per megawatt-hour *[7]*.

	Withdrawal	Consumption
Small hydro	55000	48-3800
Large hydro	20000	10-660

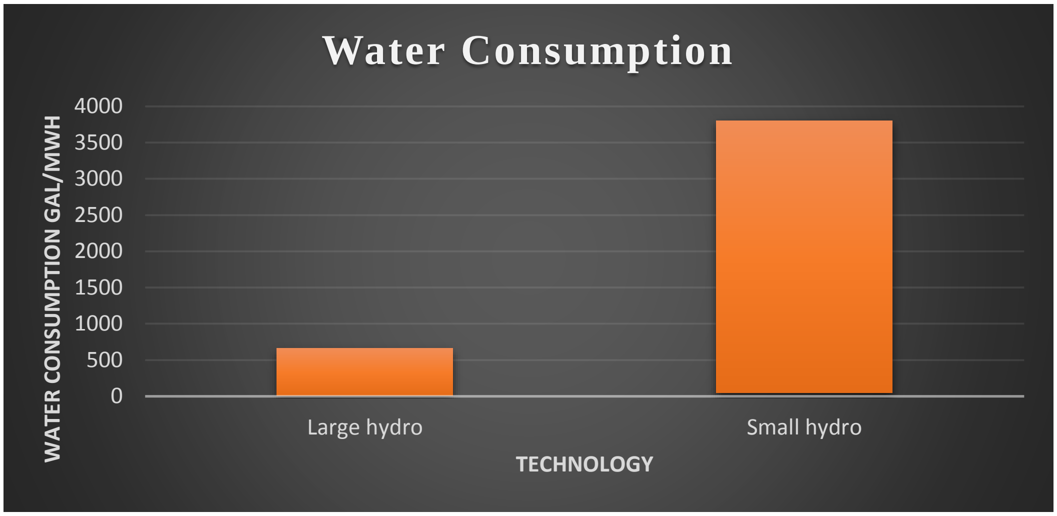

Figure 10 Water consumption of hydro technologies.

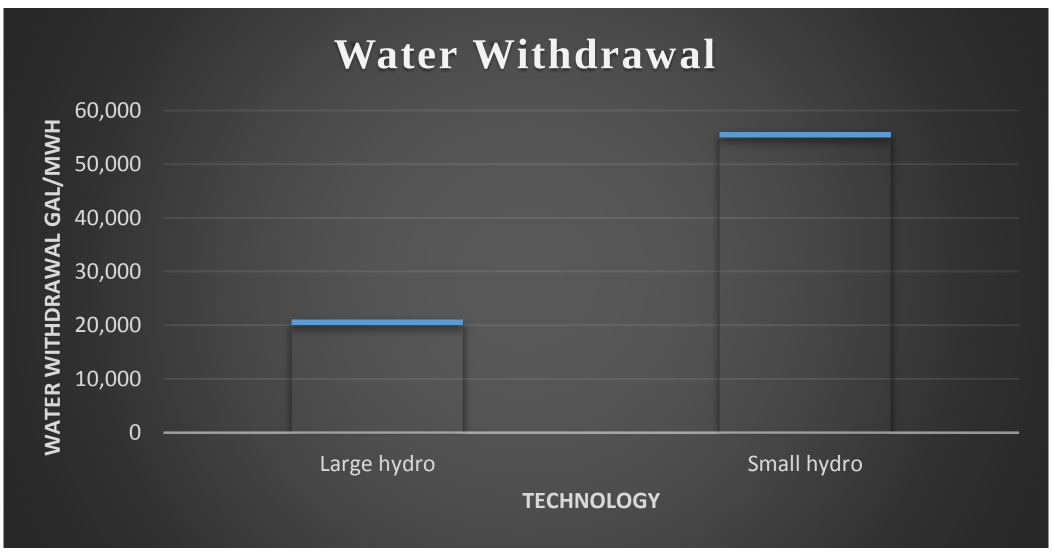

Figure 11 Water withdrawal of hydro technologies.

3-3 Nuclear:

Nuclear energy generation is satisfying 8.6 percent of California's electricity demand with only one nuclear power plant in state located in San Luis Obispo County [17].

Nuclear plants boil water into steam and use it to drive a turbine just like coal and natural gas plants do. But, the difference is that they don't burn anything. Instead, they produce the heat by splitting the atoms of uranium. Then water goes into the process. Water inters to reactor vessels and will be heated at about 300 $^{\circ}$C. for preventing from boiling at this stage it should be pressurized. Pressurized hot water goes into steam generator and will be converted to steam. In the last step this steam spins a series of turbines and generate electricity [20].

Nuclear power cycle uses water in extracting uranium and controlling waste as well as cooling process. The whole process of extracting may need about 15 gallons of water per million Btus of output. Currently there are no power plants that use dry cooling because of the safety issues that may occur.

One of the differences between a nuclear power plant and other thermal power plants is that the federal regulations require that a nuclear power plant needs to have an emergency supply of water that can cool the reactor for 30 days after it shuts down that is about 10,000 to 30'000 gallon per minute.

Finally last stage of nuclear energy generation that needs water is waste storage that needs either a water based storage pool or air cooling systems to cool down uranium fuel bundles. This stage can last as long as 15 years [21].

Table 5 Water withdrawal and consumption of nuclear in gallons per megawatt-hour *[21]*, *[9]*.

Cooling technology	withdrawal	consumption
Once through	25,000-60,000	100-400
Wet-recirculating	800-2,600	600-800
Dry cooling	N/A	N/A

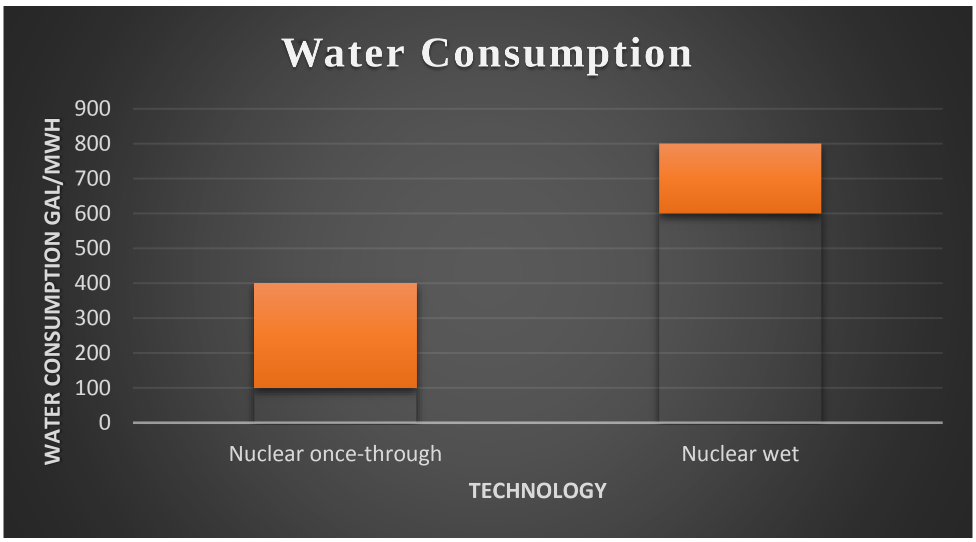

Figure 13 Water consumption of nuclear technologies.

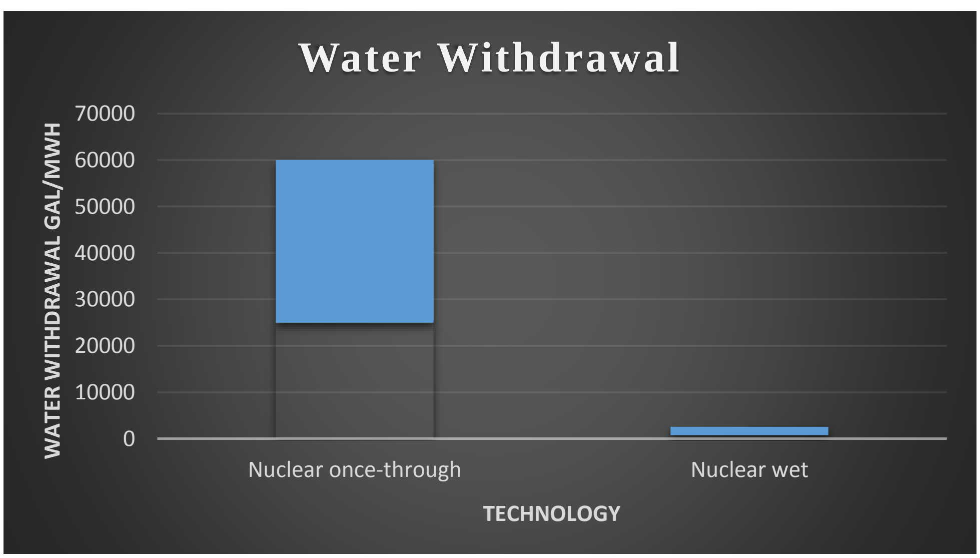

Figure 12 Water withdrawal of nuclear technologies.

3-4 Wind:

Wind power meets about four percent of the electricity demand in the entire US and California is the second largest wind power producer in United States. There are 165 wind farms in California generating about 6.5% of California's energy demand.

There is a very simple technology behind wind power electricity generation. A wind turbine uses wind to generate mechanical energy which easily can be converted to electrical energy. There are several factors that can affect the amount of energy generated in wind farms. Location, height, rotor and time of the year are the most important once [22].

The speed and force of the wind that a wind farm can get during the day is dependent to the location of the farm and time of the year. Most of the farms in California are in Tehachapi area of Kern County, with some big projects in Solano, Contra Costa and Riverside counties and they have different outputs in different seasons. In California, wind speed has its highest peak in summer. Approximately three quarters of all annual wind power output is produced during spring and summer.

Moreover, there is more wind in higher altitudes and finally the size of the rotor used in a farm is a deciding factor on the amount of energy generated. There are multiple advantages that can be mentioned about wind power generation. Wind energy produces electricity without emitting any pollutants or greenhouse gases, requires no mining, helps preserve habitat, it is cheap and easy to operate and last but not least, it needs water only for washing turbines that is very negligible compared with other sources of energy.

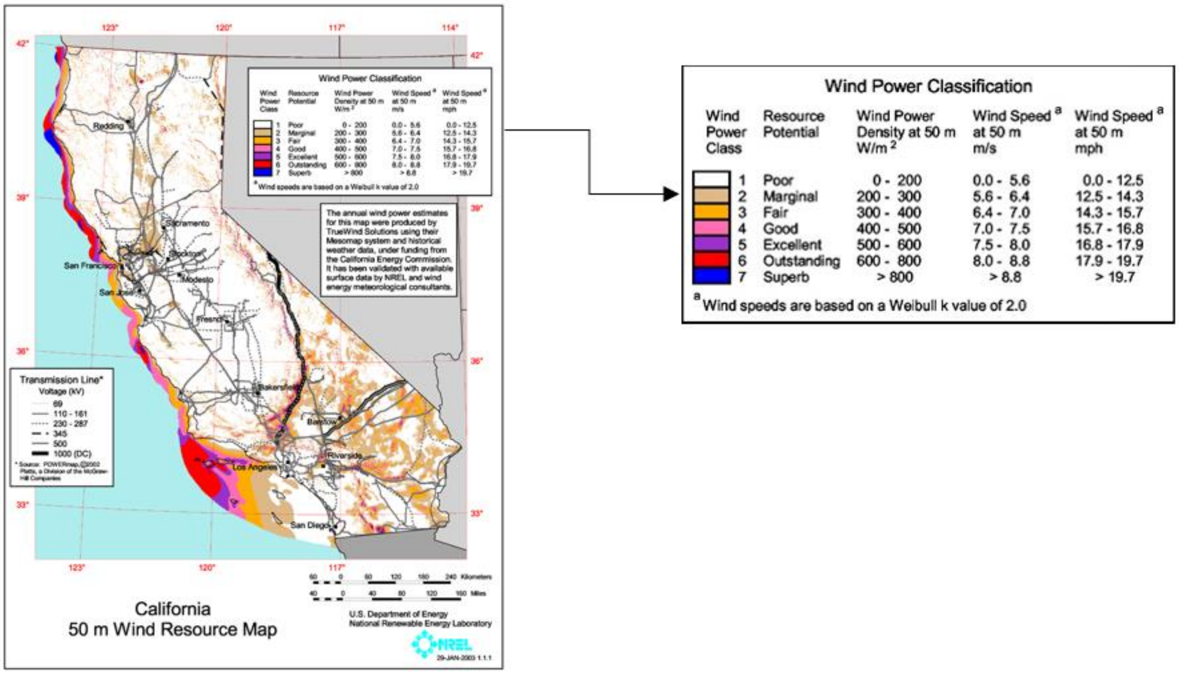

Figure 14 California wind resource map *[40]*.

The water intensity of a wind farm is greatly related to the location of the farm. Since water is only needed for washing the blades for higher efficiency, dry and dusty lands aren't qualified for a water efficient wind farm. Some regions with high volume of precipitation may not need water to wash the blades at all [7].

Generating energy with wind power in 2013 prevented the consumption of more than 35 billion gallons of water, or 285 billion bottles of water equals to saving 120 gallons per person annually. In California State, generation of 12,694 MWh electricity from wind, helped save 27,200 gallons of water [23].

3-5 Geothermal:

Geysers geothermal power plant located about 121km north of San Francisco with installed capacity of 1,517MW is the largest geothermal power plant in the world. Geysers consists of 16 separate power plant out of 45 geothermal plants total in California [24]. Geysers supplies nearly 58% of the electricity generated by geothermal power in the U.S. and 6.25% in California.

As it is clear from the name of this type of energy sources, Geo = Earth and Thermal = Heat. There are reservoirs of hot water with various temperatures and depths below earth's surface. Power plants use wells to access this natural renewable heat, a geothermal power plant receives the heat from earth to generate steam and use it to spin a turbine.

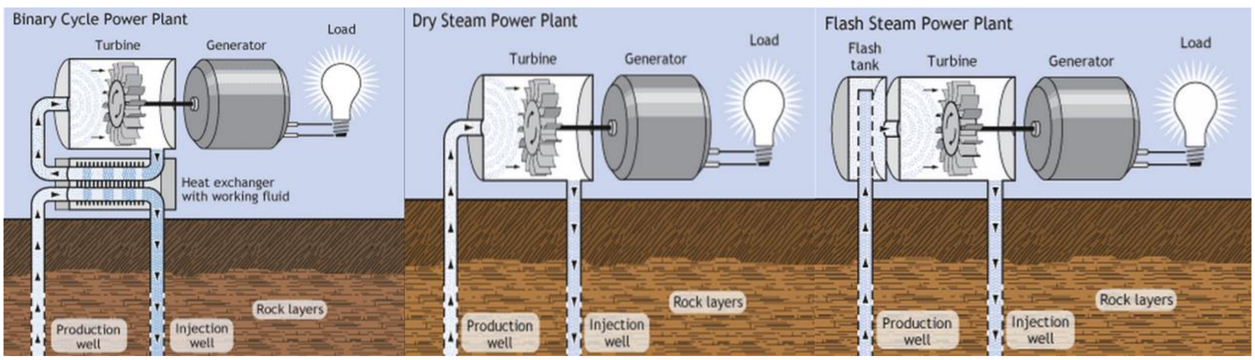

Figure 15 Different geothermal energy generation types. Image by US Department Of Energy *[7]*.

There are three types of geothermal technology. 1) Steamed power plants like Geysers draw steam directly from underground. 2) flash steam technology that pulls up the hot water with temperatures greater than 360°F through wells. The pressurized water loose its pressure on its way up and it causes the water to boil into steam. 3) Binary cycle power plants use water at lower temperatures of about 225°-360°F (107°-182°C). They use the hot water to boil a fluid, usually an organic compound with a low boiling point and as the final step these plants use the

steam to spin the turbine [25]. The majority of electricity generating geothermal units within the U.S. are binary.

All U.S. geothermal power facilities use wet-recirculating technology. Geothermal power plants consume water in two parts of the process. Extracting water from the source and cooling process. Geothermal plants can use either geothermal fluid or fresh water for cooling processes. Water is evaporated and lost when it converts to steam in the process, so power plants need to substitute this water with outside water and inject it back to the earth to make it a renewable source. But, since the reservoir water is dirty power plants like Geysers are using non-potable treated water [26].

Table 6 Water consumption in gallons per megawatt-hour [18].

Technology	Steam	Flash	Binary
Water Consumption	1796	5-19	1700-3963
Water Withdrawal	5300	5300	No Information

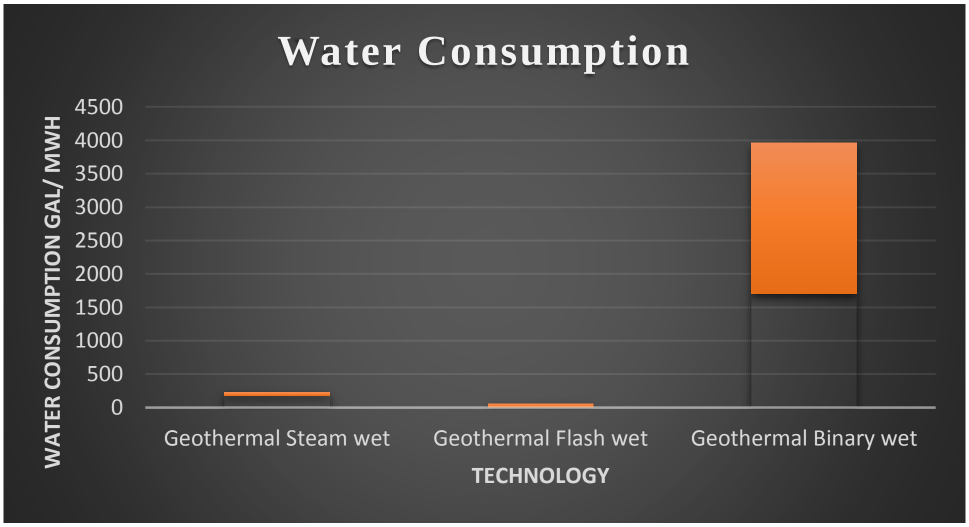

Figure 16 Water consumption of geothermal technologies.

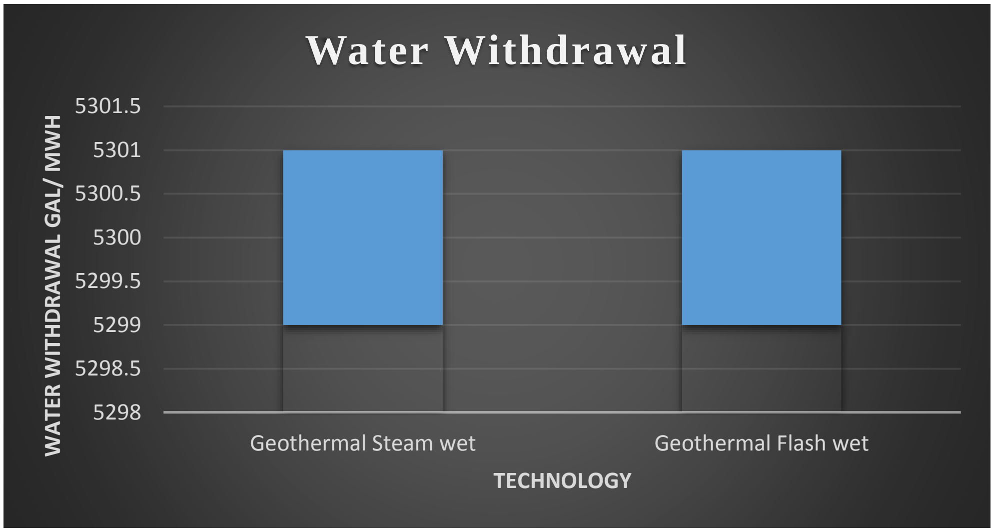

Figure 17 Water withdrawal of geothermal technologies.

3-6 Biomass:

Biomass is accounting for 3.4% of energy generation in California with 132 facilities across the state. According to the California Integrated Waste Management Board Californians create more than 2,900 pounds of household garbage and industrial waste every second; a total of 85.2 million tons of waste in 2005. Of that, half of it is recovered or recycled. Using biomass technologies, California is trying to convert about 30 million tons of the other half to energy [27].

Generally any kind of energy that is generated from a recently living organic matter or their byproducts is called bioenergy. [7] The biomass resource can be considered as renewable in which the energy of sunlight is stored in chemical bonds and when the bonds are broken by combustion or decomposition, they release their stored chemical energy.

There are different feed stocks that a biomass facility can use such as wood, agricultural crops or wastes. Some of these materials are the solution to help the environment and reduce

energy dissipation for strategies toward sustainability and energy efficiency [28]. The amount of water that each of them need for the process is significantly different. Keeping these wastes out of landfills and reducing gas emissions can be accounted as the most important advantages of generating energy through biomass.

Although there are different methods for converting biomass into electricity but most of the facilities still use the combustion of the feedstock directly to heat the water. Technologies that are applicable are dependent to the type of the feed stock. Instead of direct combustion, some new developing technologies gasify the biomass and others produce pyrolysis oils that can be used to replace liquid fuels.

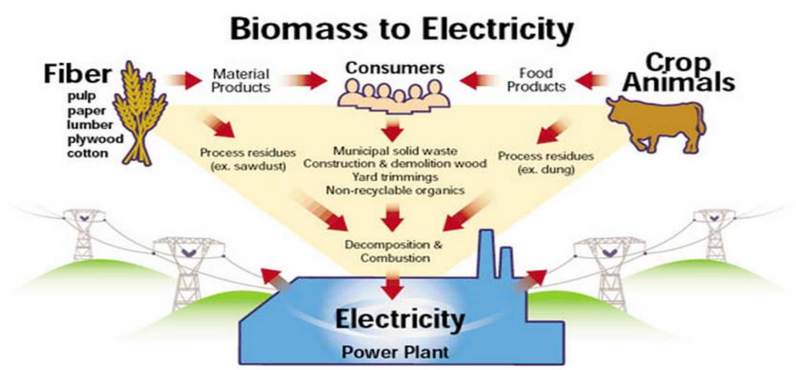

Figure 18 Biomass generating in electricity cycle *[27]*.

In addition to consuming water in the energy generation process such as cooling just like coal and natural gas power plants do, biomass facilities using crops as feedstock need a substantial amount of water for irrigating the crops. The amount of water needed in this section is dependent to the type of crops, the location of the farm and precipitation rate in that region.

Reclaimed water may be used for irrigating the crops if it doesn't have any impact on the quality of land. For saving land sometimes energy crops should be irrigated with other food crops. Reclaimed water may not be applicable in this situation. Nearly 75% of existing biomass plants use wet-recirculating technology, while 25% of plants use once-through cooling technology.

Table 7 Water consumption in gallons per megawatt-hour *[18]*, *[29]*, *[30]*.

Cooling technology	Energy generation technology	Water consumption	Water withdrawal
Once-through	Steam	300	20,000-50,000
Wet-recirculating	Steam	480-965	500-1460
Wet-recirculating	Biogas	235	250
Dry cooling	Biogas	35	50

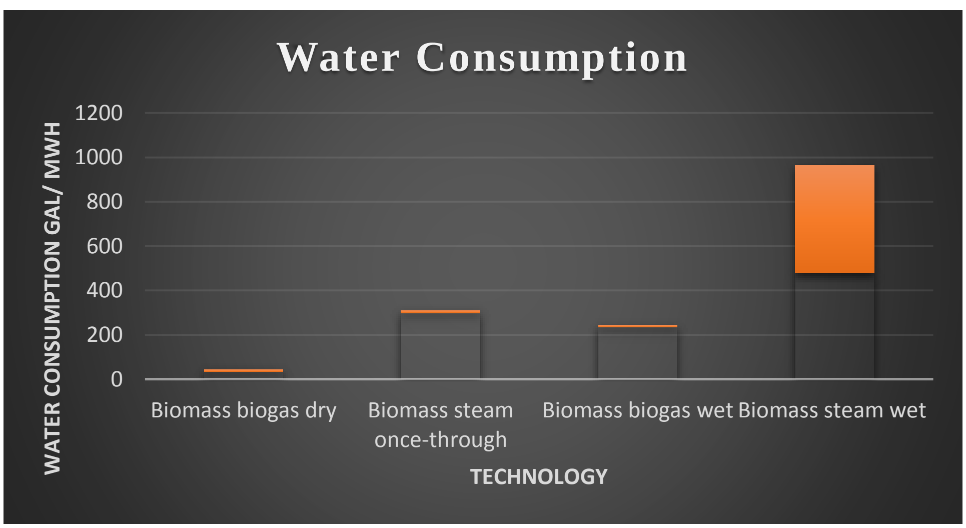

Figure 19 Water consumption of biomass technologies.

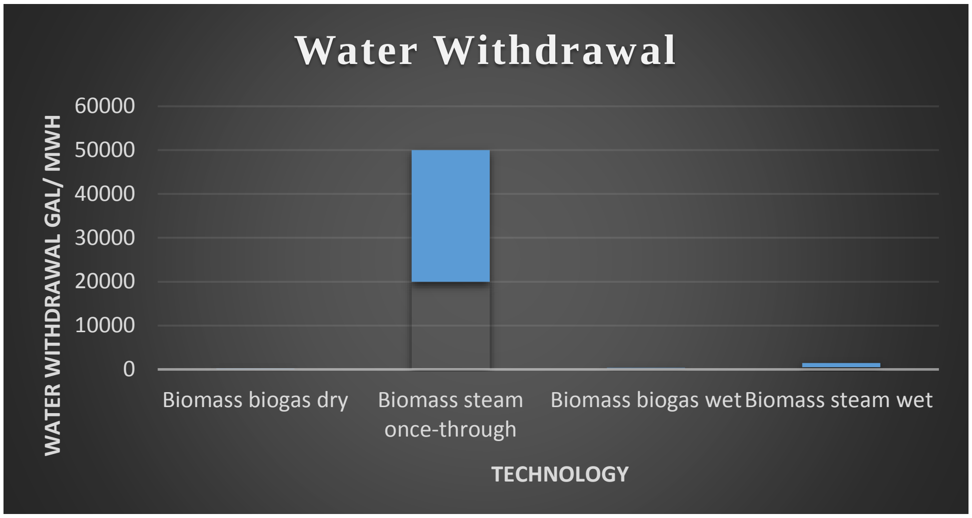

Figure 20 Water withdrawal of biomass technologies.

3-7 Solar:

There are a total of 158 solar power plant in California including the largest solar power plant in the world called Topaz power plant located in San Luis Obispo County with 9 million solar panels [31]. According to US energy administration department "California accounted for more than 75% of U.S. utility-scale solar capacity installed in 2013" and had a 3.15 percent growth from 2013 to 2014.

California launched 4,316 MW of solar electric capacity in 2013 and ranked as 1st in US. Solar is the world's fastest growing power source now. A combination of supportive solar policies and having sun in the sky for majority of days in the year make it possible for California to be the leader of solar energy in US.

There are two methods for capturing sun's energy. Photovoltaic solar use an array semiconductor to capture sun's heat and turn it directly to electricity by moving loose electrons

while thermal solar harness lower radiations with collectors to heat water or a fluid, turn it to steam and finally use it to turn a generator on.

There is a big advantage for thermal over photovoltaic solar and that is thermal solar storage. Thermal storage is using a parallel fossil fuel burner to store electricity for night and bad weather conditions, so it can eliminate the only weakness of solar energy generation.

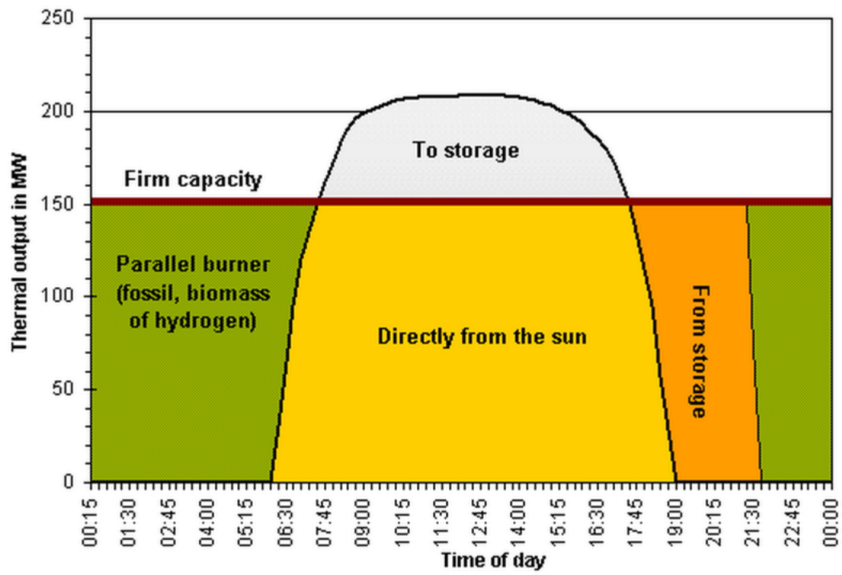

Figure 21 Solar thermal storage *[39]*.

There are two source of water consumption for solar thermal plants. They need water for cooling as well as washing collector's surface. But considering the best location for solar power plants like Mojave Desert in California, there is barely enough water for washing, so large power plants such as Ivanpah in California are using air cooled technologies to conserve water.

On the other hand photovoltaic facilities doesn't need water for cooling so, there is no concern in case of water. There is only a negligible amount of water consumption for washing

the PV cells to increase the efficiency of reflecting. In both cases using non potable water is possible and preferred.

Table 8 Water consumption of solar in gallons per megawatt-hour *[7]*, *[18]*, *[9]*.

Energy generation	Water Consumption	Water Withdrawal
Solar photovoltaic	0-33	50
Solar thermal Wet cooling	725-1109	725-1109
Solar thermal Dry cooling	43-79	43-79

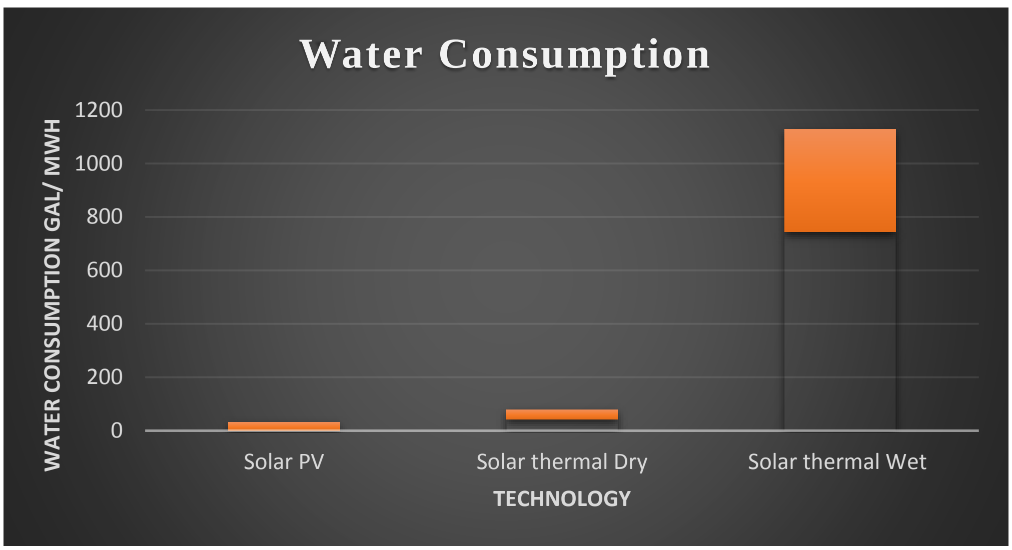

Figure 22 Water consumption of solar technologies.

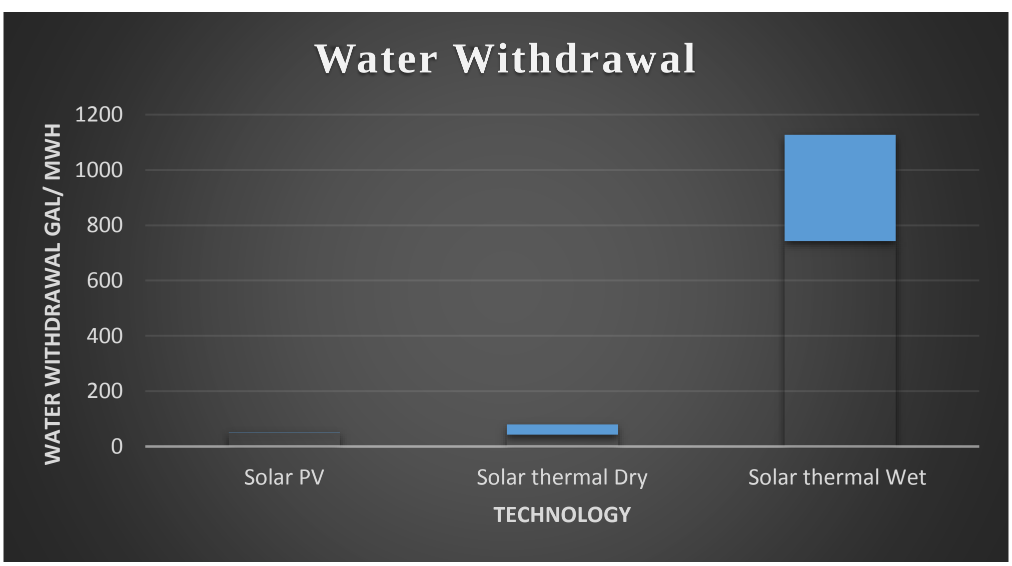

Figure 23 Water withdrawal of solar technologies.

3-8 Coal:

Although coal power has a big share in electricity generation in the entire US, about 39% of total US electricity production [32], it covers a negligible percentage of power generation in California. There are only 12 coal fired generating stations in California that are fulfilling about 0.51% of electricity demand and that's because there is no coal mining in California.

Coal fired facilities generate technology just the same way any other fossil fuel power plant does. Using combustion of the fuel to generate steam and feed a turbine with that steam to convert the mechanical energy to electricity or using the combustion to drive a generator.

Newer methods such as combined cycle with higher efficiencies are also available in some power plants. In this technology the combustion of the fuel are used directly to drive the generator and it can also produce heat to generate steam. Using the combustion in both ways make this method more efficient.

Water is needed for washing and transporting coal as well as the process of producing energy itself. The amount of water needed for washing is dependent to the method which it was mined and the amount of sulfur in it. Coal can be transferred either in the solid form by trucks or by slurry pipelines while it is mixed in the water. Cooling technologies for coal power plants are same as natural gas power plants.

Table 9 Water withdrawals for coal energy generation with different technologies [18], [9]

	Once-through	Wet-recirculating	Dry cooling
Withdrawal	20,000-50,000	500-1200	N/A
Consumption	100-317	480-1100	N/A

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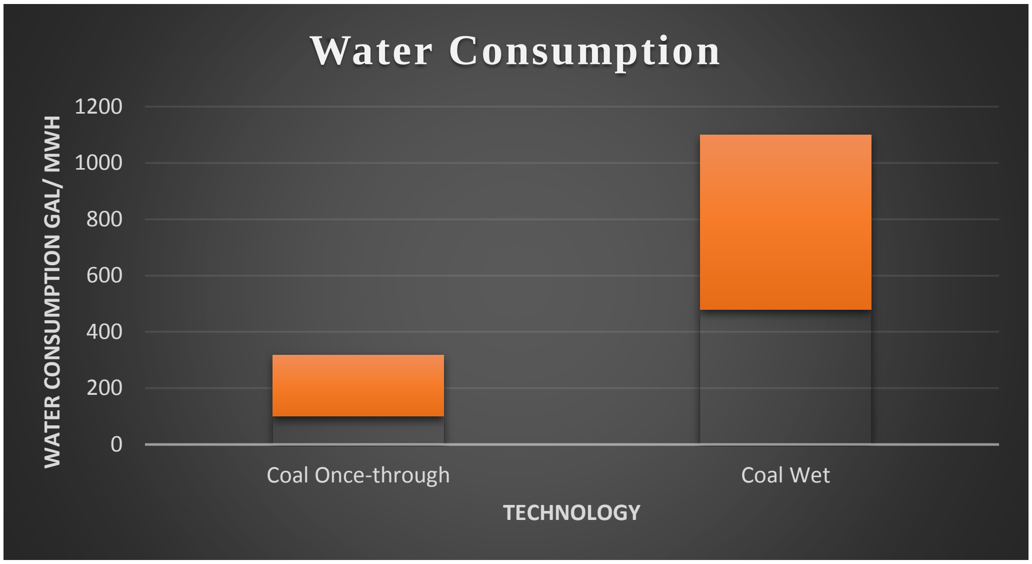

Figure 25 Water consumption of coal technologies.

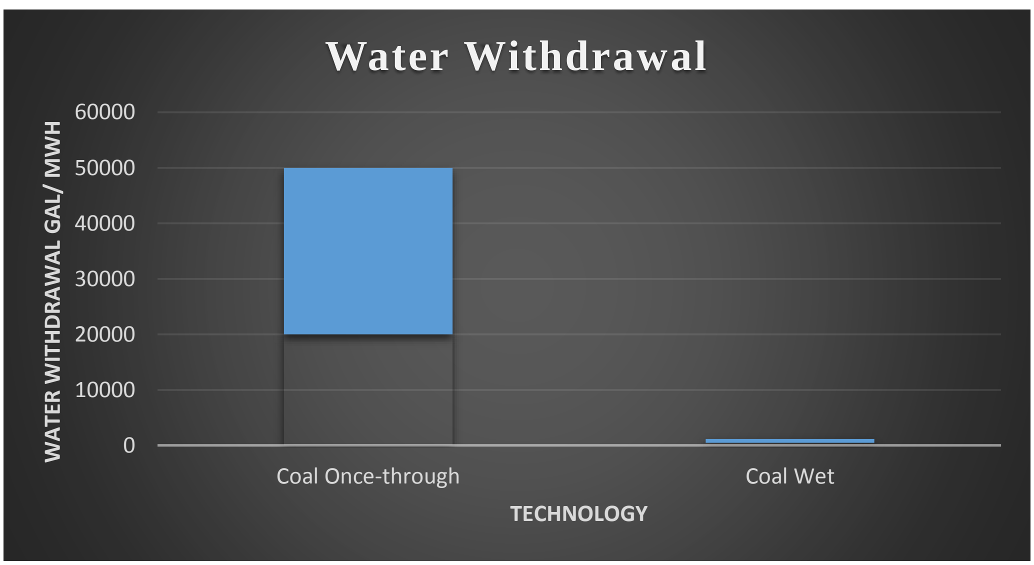

Figure 24 Water withdrawal of coal technologies.

CHAPTER 4

4- Modeling water consumption reduction

Table 10 is a summary of water intensity of all energy generation technologies based on gallons per MWh of electricity and their associated cooling technologies.

Table 10 Water consumption and withdrawal for different energy generating technologies.

Electricity generation technology	**Cooling technology**	**Variable**	**Water consumption Gal/MWh**	**Average water consumption Gal/MWh**	**Water withdrawal Gal/MWh**
Wind		X01	0	0	0
Large hydro		X_{11}	10-660	335	20,000
Small hydro		X_{21}	50-3,800	1925	55,000
Solar PV		X_{31}	0-33	16.5	50
Natural gas steam turbine	Dry cooling	X_{41}	0-4	2	0-4
Natural gas combined cycle	Dry cooling	X_{42}	0-4	2	0-4
Biomass biogas	Dry cooling	X_{51}	35	35	50
Solar thermal	Dry cooling	X_{61}	36	36	80
Natural gas combined cycle	Once through	X_{43}	20-100	60	7,500-20,000
Natural gas steam turbine	Once through	X_{44}	95-291	193	10,000-60,000
Coal	Once through	X_{71}	100-317	208.5	20,000-50,000
Nuclear	Once through	X_{81}	100-400	250	25,000-60,000
Biomass steam	Once through	X_{52}	300	300	20,000-50,000
Natural gas combined cycle	Wet-recirculating	X_{45}	130-300	215	150-283

Biomass biogas	Wet-recirculating	X_{53}	235	235	250
Nuclear	Wet-recirculating	X_{82}	600-800	700	800-2,600
Biomass steam	Wet-recirculating	X_{54}	480-965	722.5	500-1,460
Solar thermal	Wet-recirculating	X_{62}	740	740	660-830
Coal	Wet-recirculating	X_{72}	480-1100	790	500-1,200
Natural gas steam turbine	Wet-recirculating	X_{46}	662-1170	916	950-1,460
Geothermal Steam	Wet-recirculating	X_{91}	179	179	5300
Geothermal Flash	Wet-recirculating	X_{92}	5-19	12	5300
Geothermal Binary	Wet-recirculating	X_{93}	1,700-3,963	2,831.5	No Information

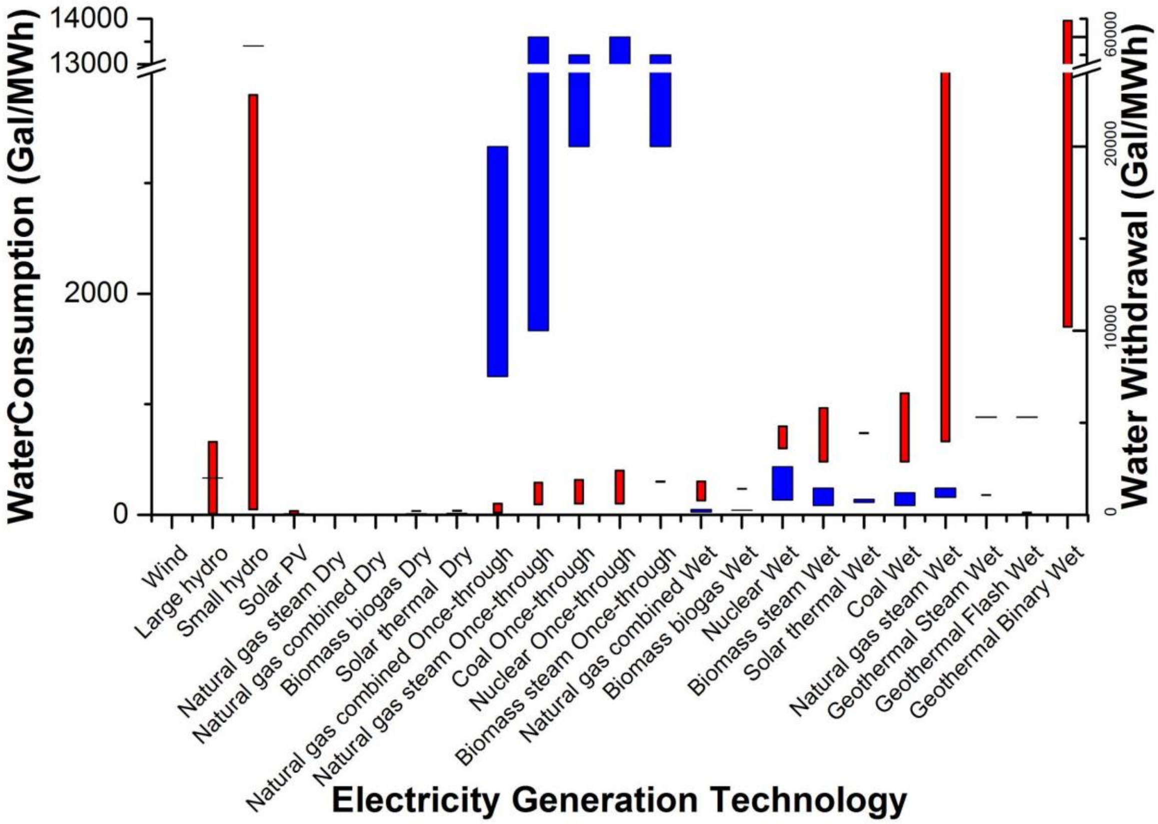

Figure 26 Water consumption and withdrawal of different energy generation technologies

Now that water consumption for all the technologies are available, we are one step ahead in making a good decision about what technology is the best to produce electricity. But first, the capacity of each technology in California is needed because, none of these technologies can produce unlimited electricity and on the other hand at least all the California demand must be served. Power plants cannot produce as much as their installed capacity.

The capacity factor that is a number between zero and one defined as “the ratio of the electrical energy produced by a generating unit for the period of time considered to the electrical

energy that could have been produced at continuous full power operation during the same period" according to US Energy Information Administration. Capacity factor highly depends on the energy source of the power plant.

Table 11 shows the capacity data provided by California Energy Commission for all existing technologies in California in 2014 and the capacity factor for each technology reported by US EIA.

Table 11 State Electric Generation Capacity by Fuel Type (GWh) and Percentage of capacity factor for different technologies [32] [33].

Generation Source	In-state Capacity	Capacity Factor %
Coal	1,463	60.9
Biomass	11,151	60.5
Geothermal	23,678	68.8
Nuclear	20,349	91.7
Natural gas	404,860	47.8
Large hydro	108,291	37.5
Small hydro	14,217	37.5
Solar PV	40,637	27.8
Solar Thermal	11,388	19.5
Wind	51,649	33.9

The capacity for 2015 is not available yet so this paper uses the demand for 2014 for finding the best technologies with the least water consumption. The average demand in 2014 was forecasted to be 295,661 GWh [16] according to a report by California Energy Commission in June 2013.

Now based on all this information, this paper offers a linear model to solve this problem. The result would be the best technologies for generating electricity to reduce the total amount of water consumed. The objective and constraints are as follows:

4-1 General model:

$$Z = \sum_{i=0,j=1}^{i=9,j=6} Wij * Xij$$

s.t.

$$\sum_{j=1}^{j=6} Xij \leq Ci * Cfi$$

$$\sum_{i=0,j=1}^{i=9,j=6} Xij \geq D$$

$$Xij \geq 0$$

Xij = amount of electricity that must be generated by electricity generation i and technology j (GWh)

Wij = average water consumption for electricity generation i and technology j (gal/GWh)

Ci = capacity of energy source i (GWh)

Cf_i= Capacity factor for energy source i

D = Average demand in state of California (GWh)

4-2 Basic numerical model:

$Z = 0*X_{01} + 335*X_{11} + 1925*X_{21} + 16.5*X_{31} + 2*X_{41} + 2*X_{42} + 60*X_{43} + 193*X_{44} + 215*X_{45} + 916*X_{46} + 35*X_{51} + 235*X_{52} + 300*X_{53} + 722.5*X_{54} + 36*X_{61} + 740*X_{62} + 208.5*X_{71} + 790*X_{72} + + 250*X_{81} + 700*X_{82} + 179*X_{91} + 12*X_{92} + 2831.5*X_{93}$

(1) $X_{01} \leq 17{,}509$

(2) $X_{11} \leq 40{,}609$

(3) $X_{21} \leq 5{,}331$

(4) $X_{31} \leq 11{,}297$

(5) $X_{41} + X_{42} + X_{43} + X_{44} + X_{45} + X_{46} \leq 193{,}523$

(6) $X_{51} + X_{52} + X_{53} + X_{54} \leq 6{,}746$

(7) $X_{61} + X_{62} \leq 2{,}221$

(8) $X_{71} + X_{72} \leq 891$

(9) $X_{81} + X_{82} \leq 18{,}660$

(10) $X_{91} + X_{92} + X_{93} \leq 16{,}290$

(11) $X_{01} + X_{11} + X_{21} + X_{31} + X_{41} + X_{42} + X_{43} + X_{45} + X_{46} + X_{51} + X_{52} + X_{53} + X_{54} + X_{61} + X_{62} + X_{71} + X_{72} + X_{81} + X_{82} + X_{91} + X_{92} + X_{93} \geq 295{,}661$

(12) $X_{ij} \geq 0$

Table 12 Results for the general model.

Energy Source	Variable	Production GWh
Wind	X_{01}	17,509
Large hydro	X_{11}	28,523
Solar PV	X_{31}	11,297
Natural Gas Steam Turbine dry cooling	X_{41}	193,523
Biomass Biogas Dry Cooling	X_{51}	6,746
Solar Thermal	X_{61}	22,20

Coal Once-Through	X_{71}	44,792
Nuclear Once-Through	X_{81}	18,660
Geothermal Flash	X_{91}	16,290
Any other technology	X_{ij} except variables mentioned above	0
Total electricity generation	**295,661 = demand**	
Electricity shortage	**0**	
Total Water Consumption	**15,492,000 gallon**	

Results for the general model

1) Based on this result all the energy sources except for hydro need to produce at their maximum capacity to meet the demand. Although large hydro still needs to produce more than half of its capacity, all the demand can be satisfied without small hydro facilities.
2) This result is also showing the best technology among all other technologies, for each energy source. For example geothermal flash is the best technology between all the methods using geothermal as a source. Although there are various technologies in different power plants, the best way to save water is to change the facilities to those methods with lowest water consumption.
3) The amount of total water consumption in this model is the lowest water consumption possible for California with this energy generation mix because, it has been assumed that the least water consuming technologies for each energy source are producing the whole capacity.

Drawbacks of the general scenario:

First of all, to reduce water intensity, most of fossil fuel power plants must switch all their cooling technologies to dry cooling. But, dry cooling is not efficient enough in hot days of summer since the heat capacity of air is not high enough and that causes the temperature of the steam to be high even after cooling. This study offers to use hybrid cooling systems to create a balance between efficiency and water consumption. Hybrid systems can increase the efficiency in hot days by using wet components while reducing water consumption in any other time of the year.

Moreover, there are a lot of aging water-intensive plants in California that are approaching their lifetime end session in this coming decade and the world is going toward more renewable and energy efficient methods.

Hydro accounts as renewable source of energy and has a lot of leverages over fossil fuel plants. But, the problem is that five consecutive dry years for California dropped a large percentage of hydro energy generation. Also, hydro facilities are disturbing the ecosystem. Hydro plants are destroying a lot of creature’s habitat and they emit a large amount of carbon dioxide and methane. Hydro facilities can have effect on agriculture and all the animals and plants that live in the river. Recently four hydro power plants on the Klamath River have been shut down by environmentalists to rescue the salmon that migrate upstream in this river and to solve the irrigation problem close to these dams for farmers. [34]

On the other hand, Shutting down Nuclear facilities is being widespread throughout the whole US especially during past two years. California is planning to phase out its only nuclear facility because, the benefits of nuclear power to California are much slighter than its risks.

Several earthquake faults, radioactive waste, high probability of catastrophic nuclear accidents and fuel availability are the most important reasons that force California's regulators to shut down their only nuclear facility [35].

The Model provided in this study has the ability to determine water consumption and the amount of shortage in demand that might occur in California for different energy generation scenarios. This next chapter is showing different case when California have no-hydro-nuclear plants, no-hydro plants and etc, and investigates how much shortage and water consumption will be associated with each plan for California.

CHAPTER 5

5- Different water reduction scenarios

5-1 No-Hydro-Nuclear plant scenario

In this scenario every constraint in the basic model stays the same except for constraint (2), (3) and (9) that would change to:

$\mathbf{X_{11} \leq 0}$

$\mathbf{X_{21} \leq 0}$

$\mathbf{X_{81} + X_{82} \leq 0}$

Table 13 Results for No-Hydro-Nuclear plant scenario.

Energy Source	Variable	Production GWh
Wind	X_{01}	17,509
Solar PV	X_{31}	11,297
Natural Gas Steam Turbine dry cooling	X_{41}	193,523
Biomass Biogas Dry Cooling	X_{51}	6,746
Solar Thermal	X_{61}	22,20
Coal Once-Through	X_{71}	44,792
Geothermal Flash(fresh water)	X_{91}	16,290
Any other technology	X_{ij} except variables mentioned above	0
Total Electricity Generation	**248,478 < demand**	
Electricity shortage	**47,183**	
Total Water Consumption	**About 1 million gallon**	

With a quick look at the total water consumption one question comes to mind. Why is there a decrease in water consumption with applying one more constraint? Usually when you add one constraint to the model, the objective gets worse. But, in this special case it didn't. The reason is, the capacity of all other electricity generations except hydro wasn't able to fulfill the demand.

Using this scenario, California can save up to 14 million gallons of water. In other words one good conclusion from this result is that 16 percent or 50,000 GWh less demand would cut the water consumption by 94 percent or 14 million gallons. What can the state do to compensate for its shortage of electricity while still keeping water consumption low?

Next scenario is considering a case when nuclear plants are still on to see if nuclear capacity is enough to fulfill the shortage and how much more water it consumes.

5-2 No-Hydro plant scenario

Every constraints in the basic model stays the same except for constraint (2) and (3) that would change to:

$$\mathbf{X_{11} \leq 0}$$

$$\mathbf{X_{21} \leq 0}$$

Table 14 Results for No-Hydro plant scenario.

Energy Source	**Variable**	**Production GWh**
Wind	X_{01}	17,509
Solar PV	X_{31}	11,297

Natural Gas Steam Turbine dry cooling	X_{41}	193,523
Biomass Biogas Dry Cooling	X_{51}	6,746
Solar Thermal	X_{61}	22,20
Coal Once-Through	X_{71}	44,792
Nuclear Once-Through	X_{81}	18,660
Geothermal Flash(fresh water)	X_{91}	16,290
Any other technology	X_{ij} except variables mentioned above	0
Total Electricity Generation	**267,138 < demand**	
Electricity shortage	**28,523**	
Total Water Consumption	**Almost 6 million gallon**	

As it is clear from the result this scenario is improving environmental issues and decreasing water intensity of the energy sector compared with the original model.

The water consumed by the whole system has been reduced to 6 million gallons. By numerical means, shutting down all hydro facilities decrease water consumption in electricity sector by 9million gallon, but it creates about 28,000 GWh shortage in the system.

5-3 Modifications to proposed scenarios

5-3-1 Importing electricity

Importing electricity from Pacific Northwest and U.S. Southwest is one option for California to compensate for its shortage. This solution may have a lot of cost including the

electricity price and transportation. Also a fraction of the transported electricity may be lost in the transportation and all of these can increase the price of electricity. The cost associated with this solution is dependent on the distance between two states and the source of the energy.

However, sometimes adjacent states generate more than their demand. In this case, there would be a penalty if they don't sell or store it. Producers pay other states to use this electricity so, transportation would be the only source of cost. Deciding on whether it is beneficial to import electricity or not needs a lot of detailed information and research.

5-3-2 Including some hydro plants scenario

To leave some of its large hydro facilities working to compensate the amount of shortage. This solution may be more applicable since, California still has its large hydro plants. So, there is no set up cost or huge capital investment. Moreover, the state cannot shut down and destroy all its large hydro facilities because it might cause a flood.

The California Energy Commission has a list of California hydro plants from 2014. According to this list Forbestown power plant with the lowest capacity, about 95 thousand GWh, between large hydro plants has the ability to fulfill the shortage. Although determining the best combination of hydro power plants to be on in this scenario is not simple because it requires a lot of information about their efficiency, location and etc.

Next scenario is showing a case when all the nuclear and small hydro plants are shut down and only one out of 71 large hydro plants is working. In this scenario every constraint in the basic model stays the same except for constraint (2) and (3) that would change to:

$$\mathbf{X_{11} \leq 95,265}$$

$$\mathbf{X_{21} \leq 0}$$

Table 15 Results for including some hydro plants scenario.

Total Electricity Generation	295,661 = demand
Electricity shortage	0
Total Water Consumption	About 17 million gallon

The results in table 15 shows that keeping large hydro plants to compensate for the shortage leads to consuming 2 million gallons more water. That is clearly worsening the problem of water-energy.

5-3-3 Increasing the capacity of wind and solar

Increase the capacity of wind and solar PV by adding more turbines and panels can be a very good solution. No cooling processes in generating electricity makes wind and solar PV the best technologies between all other electricity generation methods in the case of water consumption.

To reduce water consumption in California, electricity producers need to replace power plants which have cooling processes with renewable energy sources such as wind and solar. Well-designed wind and solar farms in California can reduce the reliance on water for electricity generation with satisfying the demand without wasting water for cooling processes.

Now the question is where to establish a new power plant? Too many parameters can effect a power plant location decision. Available land is the most important in case of solar and wind since, it must be rich in wind or sunshine and it must be large enough to fit an impressive number of panels or turbines.

For that matter researchers are investigating possible methods to combine solar and wind farms in one land. Solar-wind hybrids are common and familiar in backyard setups in the U.S. and around the world. In locations where there is no grid service or to minimize grid reliance, a combination of solar panels and a small wind turbine may capitalize on local resources [36].

The first image that comes to mind regarding the combination of solar and wind is a turbine with solar panel blades. However there are some problems associated with this type of turbines that stops researchers from applying it in the real world.

The most important issue is that the blades are located vertically, so panels would only get solar power with the sun low in the sky at sunrise or sunset while solar panels need to be pitched at an angle 30 - 45 degree for maximum optimum performance. Also, the reflection of the blades can send blinding beams of light to the airplanes [37].

On the other hand, sharing land between wind and solar sources in the configuration of figure 25 leads to a lot of benefits.

Figure 27 best configuration for a hybrid wind-solar farm *[38]*.

Here is a list of benefits for this type of configuration:

- Twice the amount of electricity being generated across the same surface area and it means two times more efficiency. Although the problem of shading caused by the shadows of wind turbines on the panels is very serious, it can be reduced to 1% - 2% in a well-designed power plant depending on the location of the land.
- There is no need for grid expansion because, the plant generates wind and solar in different times of a day and during complementary seasons [38].

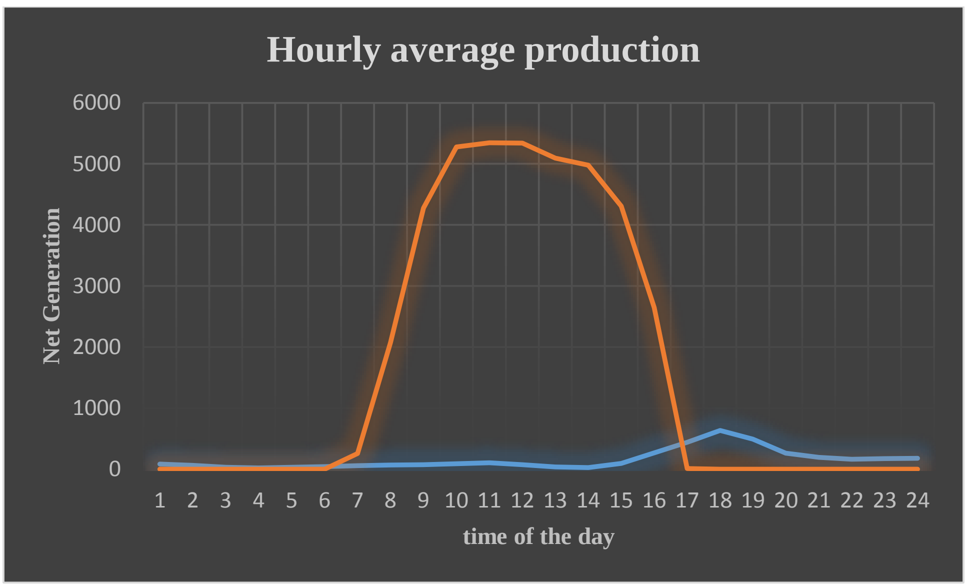

Figure 28 Hourly average production of wind and solar in California *[39]*.

Table 16 Peak time and production of wind and solar in California *[39]*.

	Peak generation time	Peak production (MW)	Peak daily production(MWh)
Solar	13:59	5430	41,247
wind	17:08	3459	67,145

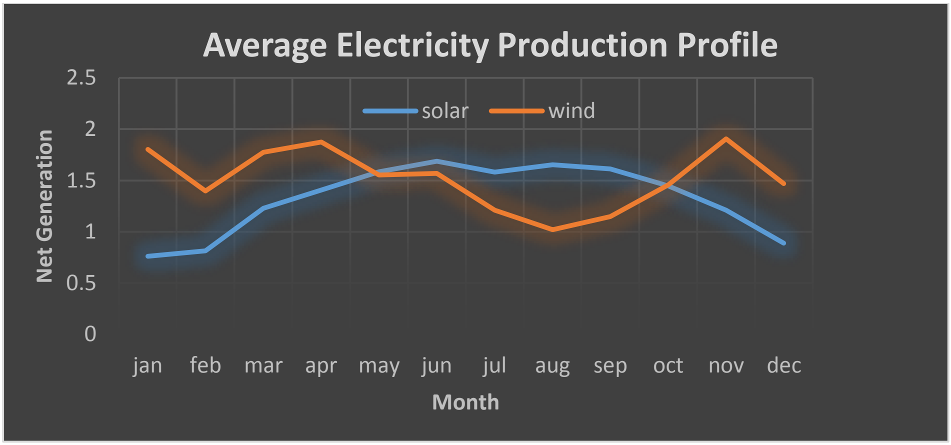

Figure 29 Average Solar and Wind Electricity Production Profile in California by Month *[39]*.

Wildflower wind and solar hybrid farm located in a uniquely sun and wind-rich Antelope valley, California, is the biggest hybrid farm in US, generating 150 MW of wind and 100 MW of solar.

According to the maps provided by California energy commission, there are some potential places especially in southern California that have the ability to be used as a hybrid farm. In the potential map for solar all the major urban areas, sensitive and inclined lands and all the areas with minimum 5 square kilometers contiguous land were excluded to identify those areas with greatest potentials for development.

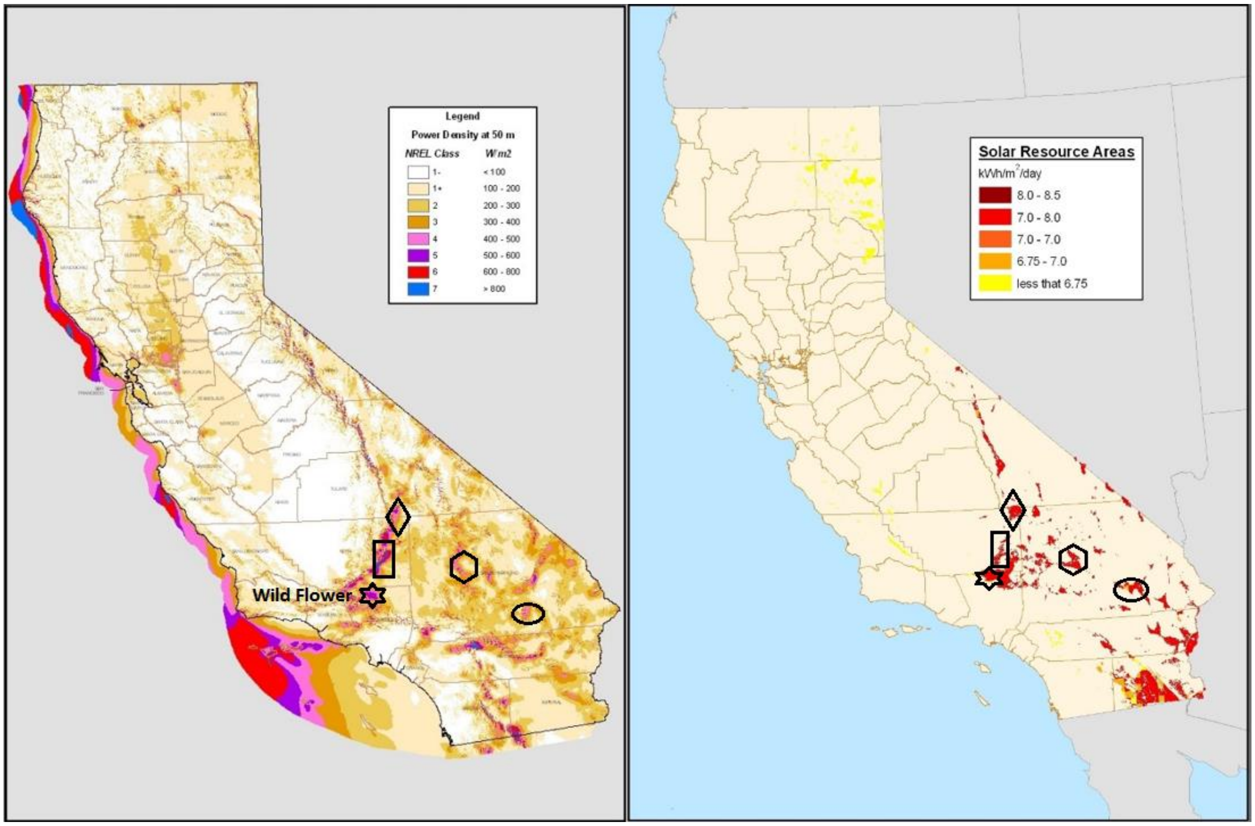

Figure 30 Map of wind and solar resource potentials in California *[40], [41]*.

As it is clear from figure 28 most of the potential lands are located in southern California. Kern, San Bernardino and a portion of Inyo County have the best opportunities to launch a new hybrid wind-solar plant. [42] Water availability is not the same all over through California. Two thirds of California's water is happened to be in the northern parts of the California while two thirds of state's population is located in southern parts, consequently there is a complexity in the water distribution system. State water project uses 12.2 billion kWh annually to transfer water to southern California and this average will increase as the population growth occurs in California [7]. Establishing new hybrid renewable farms helps southern California to produce its own electricity without relying on water.

5-4 Drawbacks of wind and solar energies:

1. **Uncertainty and unavailability:** One of the concerns associated with the renewable resources is uncertainty or unavailability of the sources. Most of the renewable energy resources are not always available. Usually, climate and geographical location have a great impact on the amount of energy generated. For instance, Wind and solar PV are both variable and intermittent in nature. The variations in wind speed results in a stochastic output for wind turbines. As a result, peak generation of wind farms and peak load demand typically do not occur at the same time [43]. Same problem is associated with solar energy generation. The exact amount of generation varies by season and the degree of cloudiness. It varies hour to hour or even minute to minute and therefore a utility may need to have backup power available to satisfy the demand for periods when solar radiation is lower than expected [44].
2. **Low capacity factor:** both wind and solar have low capacity factors and that means they can produce a small percentage of their actual capacity. For example a solar farm with 150 MW capacity is not able to generate electricity from 6 PM to 6 AM because there is no sunshine so the capacity factor for this period of time is zero percent.

Energy Storage systems can help solve these two problems by increasing the reliability of the system and picking up the shortage caused by low capacity factor.

5-5 Energy storage systems:

Shortage is not desirable in any electricity network and reliability of the networks is a very important parameter to ensure that no shortage will happen in the system. Energy storage systems absorb energy, Store it for a period of time and then release it to the energy suppliers or

power services. In this process, energy storage systems (ESSs) can be temporal time bridge. Most of the energy storage facilities store energy during low demand and low cost periods and discharge it during high peak demand. Price of energy in high peak demand periods is much higher than low demand periods. Therefore, efficient use of energy storage systems can have a great impact on the final price of electricity [45].

The main goal of storing energy is saving energy for future uses when the demands or the prices are higher or when the sources of energy are not available. Hence, using Energy Storage Systems will increase the reliability and efficiency of the system [46].

Using a hybrid network including wind and solar can increase the capacity factor of the whole system because wind and solar generate electricity in complementary times of a day and seasons but, the capacity factor for the time period between 12AM and 6AM is still very low. Energy storage systems can store energy between 10AM and 3PM that the whole network has its highest generation and release it back to the system to meet the demand during the periods that the capacity factor is close to zero.

CHAPTER 6

Conclusion:

Based on all the data collected on water intensity of all electricity generation technologies this study finds out the best methods to reduce the reliance of energy and water by minimizing total water consumption in the energy sector.

By formulating a model with the objective of minimizing water consumption, this study helps finding out the effects of different energy generation mixes that might happen to California in the upcoming decade. The results for the general model shows that California in state generation is enough to satisfy the demand with 15 million gallons of water. Wind and solar alongside all the fuel based methods with dry cooling systems have the lowest water consumption, but there are two major problems.

Most of California's fossil fuel plants need to change their cooling systems to dry cooling, while dry cooling is the least efficient cooling system since, heat capacity of air is less than water. Less efficiency means less electricity generated with same amount of water consumption. This study offers alternating hybrid cooling with dry cooling. Hybrid cooling can use wet components in hot days of summer to increase the efficiency while it can still use dry cooling in any other time of the year to decrease water consumption.

Furthermore, there are a lot of water-intensive hydro and nuclear plants in California that are serious concerns for environmentalists. In the next step, this thesis investigates water consumption of different scenarios that California is facing in the recent years. As the result for all these scenarios show, phasing out all nuclear and hydro facilities is a possible plan to reduce water intensity. No-hydro-nuclear scenario results show that 16 percent less demand in

California can cut the water consumption by 94 percent, but it needs some modifications to compensate the shortage.

Three following modifications were proposed:

1) Importing electricity: the problem associated with this solution is the price of the electricity that would be higher depending on the energy source and the distance. Energy loss also occurs during transportation.
2) Shutting down all nuclear and a portion of hydro plants: although this scenario can meet the demand but its water consumption is 2 million gallons more than general scenario that is clearly worsening the problem of water consumption.
3) Increasing the capacity of wind and solar: this can fulfill the shortage without relying on water but it needed more detail on the location of the power plant.

Since wind and solar need a large land that is rich in wind and sunshine and to fit a massive number of turbines and panels. Due to the land consuming problem of both these technologies. This paper offers a good configuration and some potential places in southern California for constructing hybrid wind-solar farms by investigating their wind speed and solar radiations. The problem of reliability and energy loss for these two renewable source can also be reduced using energy storage systems as back up.

Scope of future research:

There are a number of topics that this topic highlighted but not in details on which further research would be beneficial. Water-energy nexus is a part of some major networks such as water-energy-land and water-energy-food. Further studies might look for land and food concerns which can be added to the scenarios, modifications and limitations.

Some additional areas for further research that have been highlighted by the study undertaken for this thesis are exact location of the wind and solar farms in California and the amount of electricity that must be generated by them to fulfill the shortage which can be discussed in more details. Moreover best energy storage systems that can be coupled with renewable sources to solve the problem of reliability and energy loss can be an interesting topic for future research.

References

[1] "The Connections Between Our Energy and Water," Union of Concerned Scientists, [Online]. Available: http://www.ucsusa.org/clean_energy/our-energy-choices/energy-and-water-use/energy-and-water.html#.VNj2QfnF_UV.

[2] EIA, WATER FOR ENERGY, MITCHELLE BOWMAN, 2012.

[3] "california's water-energy relationship," California Energy Commission, 2005.

[4] "EPA water news," US EPA, [Online]. Available: http://water.epa.gov/.

[5] S. Hendrick, "OVERVIEW OF THE WATER-ENERGY NEXUS IN THE UNITED STATES," in NCEL, 2014.

[6] Electric Power Research institute, "Comparison of Alternate Cooling Technologies for California Power Plants," California Energy Commission, 2002.

[7] B. Dennen, D. Larson, C. Lee and S. Tellinghuisen, "California's Energy-Water Nexus: Water Use in Electricity Generation," 2007.

[8] W. Mills, A. Gabriel and D. Gabriel, "Viability and Impacts of Implementing Various Power Plant Cooling Technologies in Texas," EPRI, texas, 2012.

[9] "How it Works: Water for Power Plant Cooling," Union of Concerned Scientists, [Online]. Available: http://www.ucsusa.org/clean_energy/our-energy-choices/energy-and-water-use/water-energy-electricity-cooling-power-plant.html#bf-toc-0.

[10] s. bushart, "Advanced Cooling Technologies for Water Savings at Coal-Fired Power Plants," 2014.

[11] D. Mishra and S. Agarwal, Operation Research, Word Press, 2009.

[12] "About Operations Research," INFORMS, 2012.

[13] L. V. Kantorovich, "A new method of solving some classes of extremal problems," Doklady Akad Sci USSR, vol. 28, pp. 211-214, 1940.

[14] F. L. Hitchcock, "The distribution of a product from several sources to numerous localities," 1941.

[15] M. Nyberg, "Total Electricity System Power," California Energy Commission, 10 09 2015. [Online]. Available: http://energyalmanac.ca.gov/electricity/total_system_power.html.

[16] "Final California Energy Demand Forecast 2012-2022," California Energy Commission,

California, 2013.

[17] "california power plants," California Energy Commission, Energy Alamanac, california, 2014.

[18] J. Macknick, R. Newmark, G. Heath and K. Hallet, "Operational water consumption and withdrawal factors for electricity generating technologies," National Renewable Energy Labratuary, 2011, 2012.

[19] Energy Aware Planning Guide, california energy commission.

[20] "How electricity is generated through nuclear power," EDF energy, [Online]. Available: http://www.edfenergy.com/energyfuture/generation-nuclear.

[21] "How it Works: Water for Nuclear," Union of Concerned Scientists, [Online]. Available: http://www.ucsusa.org/clean_energy/our-energy-choices/energy-and-water-use/water-energy-electricity-nuclear.html#.VOY7NfnF_UU. [Accessed 2015].

[22] "What factors affect the output of wind turbines?," alternative energy, 24 July 2009. [Online]. Available: http://www.alternative-energy-news.info/what-factors-affect-the-output-of-wind-turbines/.

[23] "Wind Energy Conserving Water," American Wind Energy Association, 2013. [Online]. Available: http://www.awea.org/windandwater.

[24] "The top 10 biggest geothermal power plants in the world," 2013. [Online]. Available: http://www.power-technology.com/features/feature-top-10-biggest-geothermal-power-plants-in-the-world/.

[25] "Geothermal Electricity Production," renewable energy world, 26 02 2015. [Online]. Available: http://www.renewableenergyworld.com/rea/tech/geothermal-energy/geoelectricity.

[26] "How Geothermal Energy Works," Union of Concerned Scientists, 22 12 2014. [Online]. Available: http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/how-geothermal-energy-works.html#.Vij2PvlViko.

[27] P. Sethi, "Waste to Energy & Biomass in California," california energy commission, [Online]. Available: http://www.energy.ca.gov/biomass/.

[28] E. Omrani, A. Dorri Moghadam, P. L. Menezes and P. K. Rohatgi, "influences of graphite reinforcment on the tribological propertise of self-lubricanting aluminum matrix composites for green tribology ,sustainability, and energy efficiency- A review," Int J Adv Manuf Technol, 2015.

[29] "Environmental Impacts of Biomass for Electricity," Union of Concerned Scientists,

[Online]. Available: http://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/environmental-impacts-biomass-for-electricity.html#bf-toc-0.

[30] R. Goldstein and W. Smith, "U.S. Water Consumption for Power," EPRI, 2002.

[31] J. Richardson, "World's Largest Solar Power Plant Is Now In Operation," clean technica, 02 12 2014. [Online]. Available: http://cleantechnica.com/2014/12/02/worlds-largest-solar-power-plant-now-operation/.

[32] "Electric power monthly," US Energy Information Administration, 2014.

[33] M. Nyberg, "Electric Generation Capacity & Energy," 2014. [Online]. Available: http://energyalmanac.ca.gov/electricity/electric_generation_capacity.html.

[34] J. Erikson, "GREEN VS GREEN," Breitbart, 26 april 2012. [Online]. Available: http://www.breitbart.com/big-government/2012/04/26/green-vs-green-environmentalists-win-fed-backing-to-shut-down-hydro-power/.

[35] M. Brooks, "Nuclear Energy Pros and Cons," Conserve Energy Future, [Online]. Available: http://www.conserve-energy-future.com/pros-and-cons-of-nuclear-energy.php.

[36] H. K. Trabish, "One Solar-Wind Hybrid Goes Down, Another Goes Up," green tech media, 22 januery 2012. [Online]. Available: http://www.greentechmedia.com/articles/read/one-solar-wind-hybrid-goes-down-another-goes-up.

[37] G. Mitchell, "focus science and technology," BBC Focus, July 2009.

[38] D. LUDWIG, "Wind-solar hybrid plants up to twice as efficient," PV Magazine, 22 april 2013.

[39] "renewables watch," California ISO, 2015.

[40] "Dynamic maps, GIS data and analysis tools," National Renewable Energy Laboratory, January 2007. [Online]. Available: http://www.nrel.gov/gis/data_wind.html.

[41] "California Energy Maps," California Energy Commission, 2010. [Online]. Available: http://www.energy.ca.gov/maps/.

[42] N. Nouri, M. H. Balali and A. Nasiri, "Water withdrawal and consumption reduction analysis for electrical energy generation systems," journal of environmental studies and sciences, the food-energy-water nexus, no. march, 2016.

[43] A. Nasiri and A. Esmaili, "Evaluation of impact of energy storage on effective load carrying capability of wind energy," IEEE, p. 6, 2012.

[44] E. M. Mazaheri, J. Zhao, N. Koyuncu, V. Kachanovskaya and B. lyons, "Study of compressed air energy storage with grid and photovoltaic energy generation," The Arizona

Research Institute for solar energy, 2010.

[45] M. H. Balali, N. Nouri, A. Nasiri and H. Seifoddini, "development of an economical model for a hybrid system of grid, PV and energy storage systems," in ICRERA, 2015.

[46] I. Avdeev and M. Gilaki, "Structural analysis and experimental characterization of cylindrical lithium-ion battery cells subject to lateral impact," Journal of Power Sources, 2014.

[47] "water-energy opportunities," California sustainability alliance, [Online]. Available: http://sustainca.org/programs/water_energy/opportunities.

[48] "US drought monitor," 03 02 2015. [Online]. Available: http://droughtmonitor.unl.edu/Home/RegionalDroughtMonitor.aspx?west.

[49] S. Tellinghuisen, Writer, water required for electricity production. [Performance]. 2007.

[50] l. pyn, vancouver sun, 20 march 2013. [Online]. Available: http://www.buteinlet.net/.

[51] l. baumann, penn energy, 5 sep 2014. [Online]. Available: http://www.pennenergy.com/articles/pennenergy/2014/09/montana-regulators-advance-900mm-hydroelectric-power-purchase.html.

[52] m. lucky, world watch institute, 28 03 2012. [Online]. Available: http://blogs.worldwatch.org/revolt/pump-up-that-seawater-a-remix-to-pumped-storage-hydro/.

[53] "electric power monthly," US energy information administration, 2015.

[54] V. Quaschning, "Solar thermal power plants," Renewable Energy World, vol. 6, 2003.

[55] J. Orwig, "Alarming charts show how fast California is losing its water," Business Insider, 02 04 2015. [Online]. Available: http://www.businessinsider.com/californias-drought-situation-is-worse-than-ever-2015-4.

[56] M. Bowman, "Today in Energy," US Energy Information Administration, 06 10 2014. [Online]. Available: https://www.eia.gov/todayinenergy/detail.cfm?id=18271.

[57] E. Mielke, L. D. Anadon, V. Narayanamurti and B. Pierce, "Water Consumption of Energy Resource Extraction, Processing, and Conversion," 2010.