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FINAL PROJECT REPORT

Estimates of Groundwater Pumping Electricity Use and Costs in California

Prepared for: **California Energy Commission**
Prepared by: **Lawrence Berkeley National Laboratory**

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[1] Some TAC members may currently have a different affiliation than when they joined the Committee.

PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Report title is the final or interim report for the project "Projecting Near-Term Groundwater Pumping Energy Use and Costs in California to Improve Energy and Water Systems Reliability," Agreement EPC-15-035, conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

The goal of this project was to bridge a key knowledge gap in California's energy-water interactions: the electricity required to pump groundwater in the state. This project offers a comprehensive look at how energy and groundwater interact in California and provides a basis for estimating energy demand for groundwater pumping in the near term under alternative climate and policy scenarios. The study is organized into four parts. The first part identifies the groundwater pumping data, as well as other information necessary to estimate the energy required to pump groundwater. The second part applies that data to estimate relevant empirical relationships between the factors that determine the energy required to pump groundwater. The fourth part surveys groundwater pumpers on their current groundwater pumping practices and assesses the barriers to and incentives for improving energy efficiency and water conservation with groundwater pumping. Finally, this report uses relationships developed during the project to estimate near-term groundwater pumping energy uses and costs across the state, under alternative climatic conditions. It further applies findings from the third part of the study to a simulation of how estimated energy and its cost could be reduced with enhanced pump-energy efficiency and water-conservation measures.

Results from the larger study enable stakeholders such as state agencies, electric utilities, water planners, and large pumped-water users to develop robust projections of the energy use and cost of groundwater pumping, as well as strategies to reduce both groundwater use and energy costs in the state. Overall, the expanded knowledge provided by the study supports more cohesive energy-water planning efforts in California, particularly in light of more frequent prolonged-drought conditions.

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EXECUTIVE SUMMARY

Introduction

California pumps groundwater to meet a substantial share of its overall water requirements. While it varies from year-to-year, groundwater supplies an average of 40 percent of the water consumed by municipalities and agriculture, and nearly all Californians rely on groundwater as some portion of their water supply. Despite the vital role groundwater plays in fueling the state's economy, current pumping practices and their implications for energy demand are not well understood.

Significant knowledge gaps in the extent and efficiency of groundwater pumping prevent accurate resource planning. The energy footprint of groundwater is additionally greater than that of surface water and increases with falling water tables during drought and periods of heavy use. Adding to that concern, electricity costs in California are well outpacing those of other states. Rising groundwater use, coupled with higher electricity prices and falling groundwater levels, means that the amount of money spent on groundwater pumping will also rise in the next 20 to 30 years.

Project Purpose

This report is the third component of a study that estimates grid electricity requirements and their cost for groundwater pumping, under a range of spatial and temporal scopes and climatic and policy conditions. Lacking detailed groundwater monitoring data, it was critical that researchers estimate historic and future groundwater pumping requirements to determine electricity demand.

The first document in this series of reports presents the conceptual data analytical framework (or model) that project researchers developed to support estimates of groundwater pumping and its associated energy use. The report further describes the information the team gathered to support those estimates, as well as the sources of that information. The first report additionally describes special data preprocessing and refinements that the team used to account for missing data and scope adjustments. The first report appears as Chapters 2 to 4 in APPENDIX A of this document.

The second report describes analyses performed to assess how climatic conditions, cropping patterns and agricultural water use, demographics and urban water consumption, pumping technology, pump fuels, and electricity rates can together predict the amount of groundwater to be pumped in a specific year, along with its associated grid electricity requirements and costs. The patterns and temporal trends in those relationships identified in the second report informed development of the model used in this report to estimate historic and future groundwater pumping and grid electricity use and costs. The second report appears as Chapter 5 and Chapter 6 in APPENDIX A.

The fourth report presents the results of surveys and interviews with individuals, organizations, and agencies involved with groundwater pumping to understand current groundwater pumping practices and efficiency actions from the perspective of each of these populations, as well as perceived barriers to improving both the energy efficiency of agricultural groundwater pumping and water-conservation measures.

Approach

This project estimates grid electricity use and its cost to pump groundwater. It also describes the model the team developed to support these estimates, as well as the data and assumptions that underlie the model. The model is based upon a data framework that explores the interactions that determine the amount of energy required to pump measurable amounts of groundwater. Overall, the data framework represents the key drivers of water demand: water requirements by sector (including agriculture, municipal), water sources, dynamics of groundwater levels, fuels used to pump groundwater, pumping efficiency, and electricity rates.

Urban water demand was estimated by population and urban landscape areas, while agricultural water demand was estimated by irrigated acreage. The water was then assigned by crop, climatic condition, and irrigation method. Water-supply estimates for industrial, commercial, and other uses were also factored in. Surface water availability, subject to hydrological conditions, determined the required volume of groundwater; the volume of groundwater pumped, combined with the hydrogeological characteristics of the aquifer where the pumping occurs, were then compiled to estimate changes in groundwater levels.

Groundwater-level data, combined with assumptions about drawdown and friction losses, together define total dynamic head, which is the distance groundwater must be lifted to reach the ground's surface. Total dynamic head, in conjunction with the volume of groundwater pumped and pumping efficiency, determine groundwater energy requirements. Groundwater energy, combined with the grid electricity consumed for groundwater pumping, then determines grid-electricity requirements. Finally, grid-electricity requirements and electricity rates determine the electricity cost of groundwater pumping. These interrelationships together form the basis for past and future estimates of both grid electricity consumption and the ultimate cost of pumping groundwater in California.

These estimates were developed for California Department of Water Resources planning areas, which are aggregated into hydrological regions, and submitted to electric utilities based on their service territories. Planning areas are small subdivisions of counties and reflect local hydrologic conditions. Planning area results are aggregated into the 10 hydrologic regions that correspond to the state's major hydrologic drainages.

Two groups of scenarios were developed to project groundwater total energy, grid electricity use, and costs. The first group was comprised of three sets of hydrological scenarios, each representing wet, normal, and dry climatic conditions. While the hydrological scenarios that include only years with normal hydrological conditions establish a baseline for projections, the wet and dry scenarios define a range that provides a lower (wet scenario) and an upper (dry scenario) bound for these projections. The other group of scenarios is related to changes in the main drivers of groundwater energy (e.g. agriculture and municipal indoor/outdoor water use, pumping efficiency), and was used to test which measures could effectively reduce that energy. One additional scenario assumed full electrification of well pumps, with significant contributions from solar and other renewable energy sources to power those pumps.

Conclusions

Groundwater pumping and its embedded energy vary significantly across the state. The largest use of groundwater grid electricity is in the Central Valley and is associated with the region's agriculture. Pacific Gas and Electric Company, Southern California Edison, and other electric utilities in the state are all affected by groundwater pumping. This is not only because of the size of the territories they serve but also because of agriculture in their respective service territories. Groundwater energy use is affected by changes in hydrological conditions, mostly in the North Coast, Tulare Lake, North Lahontan, South Lahontan, and South Coast hydrological regions.

The three hydrological regions that require most of the energy used to pump groundwater in the state are Tulare Lake, San Joaquin River, and Sacramento River. These three hydrologic regions comprise the Central Valley, which is an agricultural region. In normal hydrological years, the region is projected to use an annual average of 6.8 TWh of grid electricity, while the rest of the state is projected to use 2.0 terawatt hours (TWh) annually. In drier years, the region is projected to use an annual average of 9.0 TWh of grid electricity, and the rest of the state 2.9 TWh. Because groundwater use during dry periods is projected to increase in the rest of the state more than proportionally than the increase in the three hydrological regions, the share of groundwater grid electricity in the Central Valley declines from 78 percent to 76 percent when the electricity used during normal hydrological years is compared with drier years. The hydrological region most sensitive to hydrological conditions is North Coast, followed by Tulare Lake, North Lahontan, South Lahontan, and South Coast. The total projected cost of grid electricity for groundwater pumping is $15.6 billion under normal hydrological conditions. This cost drops to $13.2 billion in the wet scenario and increases to $21.3 billion in the dry scenario. The rate of economic growth may also either decrease or increase these costs by around 1 percent.

Several assumptions are made to verify which measures, and to what extent, each measure could reduce groundwater pumping energy: reducing municipal indoor and outdoor water use, and increasing irrigation and well-pumping efficiency. The measure offering the greatest opportunity for groundwater pumping energy reductions is improving irrigation efficiency, which reveals that agriculture should be the main target for reducing groundwater energy. The hydrological region with the largest opportunity to reduce electricity for groundwater pumping by improving irrigation efficiency is Colorado River, followed by San Joaquin River, Tulare Lake, and South Coast. Reducing per-capita indoor water use in the South Lahontan hydrological region, and improving pumping efficiency in the Sacramento River, South Lahontan, South Coast, and San Francisco hydrological regions (to the best-practice level in each region) can also reduce groundwater energy use. Full electrification of well pumps has very little impact on projected grid electricity supplied by electric utilities. Transitioning to all-electric well pumps, while increasing the penetration of electric well pumps powered by solar or other renewables, would increase grid electricity use over the projected period by only 1.5 percent.

The team translated projected grid electricity use at the hydrological-region level, and into grid electricity supplied by the state's electric utilities based on their respective service territories. Table 17 and Table 18 present these results. Pacific Gas and Electric Company, Southern California Edison, and San Diego Gas & Electric, as the state's largest investor-owned utilities, are the most impacted utilities. This can be explained not only by the size of their territories but also by the enormous agriculture cultivation in those service territories; over a third of the country's vegetables and three-quarters of the country's fruits and nuts are grown in California. These are therefore the utilities that would most benefit from improving irrigation efficiency that reduces groundwater grid electricity consumption. Electrification of well pumps did not appear to adversely impact the state’s electric utilities.

CHAPTER 1: Introduction

The energy consumed by California's water sector makes up an estimated 19 percent of the state's total annual electricity demand (Copeland and Carter, 2017). It is, however, largely unknown what percentage of that energy is used specifically for groundwater pumping, although efforts at assessment have begun since enactment of the state's 2014 landmark *Sustainable Groundwater Management Act,* which set forth a statewide framework to help protect groundwater resources over the long term. Pacific Gas and Electric Company's (PG&E) Advanced Pumping Efficiency Program (APEP), for example, estimates that of the agriculture's 8-percent share of statewide energy use, 70 percent can be attributed to groundwater pumping (PG&E, 2015). The estimate, however, excludes pumping conducted for other purposes, such as municipal water use.

California relies on groundwater to meet a substantial share of its overall water requirements. While it varies annually, groundwater supplies an average of 40 percent of the water consumed by municipalities and agriculture together. Approximately 85 percent of Californians rely on groundwater for some portion of their water supply (Chappelle and Hanak, 2017). Despite groundwater's critical role in the state's economy and environmental health, current pumping practices and, specifically, their implications for energy demand, are not well understood.

Significant knowledge gaps in the extent and efficiency of groundwater pumping prevent accurate resource planning. The energy footprint of groundwater is also greater than that of surface water and increases with dropping water tables during times of drought and heavy pumping. Adding to this concern, California's electricity prices are outpacing those in other states, and increased at more than five times the national average between 2011 and 2017 (Nelson and Shellenberger, 2018); these rates are projected by the United States Department of Energy's (DOE) Energy Information Agency (EIA) to grow in the Pacific Region by 42 percent by 2050. Rising groundwater use, together with higher electricity prices and falling groundwater levels, means that money expended on groundwater pumping could rise considerably over the next 20 to 30 years. While several initiatives to reduce groundwater energy use do exist, social barriers, program incentives, and potential options for overcoming those barriers are poorly understood.

This report presents the third component of a larger study that estimates electricity consumption and other costs associated with groundwater pumping for a range of spatial and temporal scopes and climatic and policy conditions. It describes the model developed and the data and assumptions that underlie the model. It further explores results from the model that estimate historical (2005-2015) and projected (2020-2030) total energy and grid electricity use and the costs of pumping groundwater in California.[2] Projections are presented for three sets of hydrological scenarios and include alternative assumptions about future water use, groundwater pumping efficiency, well-pump electrification, and electricity rates.

[2] Estimates developed in 2019.

The model also assesses how variables associated with the energy required to pump groundwater relate to one another. Empirical relationships implemented in the model are described in APPENDIX A. The relationships are organized into two groups. The first group is associated with groundwater extraction estimates. Relationships in this group refer to estimates of agriculture, municipal and other water requirements, and the conjunctive use of surface water, reclaimed (reused/recycled) water, and groundwater to satisfy those requirements. The second group focuses on the dynamic changes in groundwater levels and trends in well-pumping efficiency, and further includes relevant information about both the fuels used to pump groundwater and electricity rates. These relationships together allow for past and future estimates of grid electricity use and its costs to pump groundwater in California.

Chapter 2 presents the model the team developed, with its underlying conceptual data, analytical framework, and architecture. Chapter 3 describes the data used and assumptions made relating to water use and supply, total dynamic head, well-pumping efficiency and fuel, and electricity rates. Chapter 4 presents and discusses past (2005-2015) and projected (2020-2030) estimates of total energy and grid electricity use and its costs for groundwater pumping, at the hydrological-region level. Chapter 5 concludes with the main findings and limitations of estimates presented in this research.

CHAPTER 2: Model Description

California largely depends on groundwater to meet its water supply requirements, and concerns with the energy implications of such dependence are not new. The issue has been addressed by previous research with a range of approaches and methods.[3] This study resembles studies developed by Burt, Howes, and Wilson (2003) and Park et al., (2010). It relies on a bottom-up modeling approach; The micro- and meso-level data described in Chapter 3 of APPENDIX A, and the relationships and patterns evaluated and described in Chapter 5 of APPENDIX A, to estimate grid electricity use and costs for groundwater pumping in California. The amount and cost of grid electricity required to pump groundwater were calculated from:

$$c = r.e \qquad [1]$$

$$e = s.g \qquad [2]$$

$$g = \frac{gw.h}{u}.k \qquad [3]$$

where:

- c is the grid electricity cost.
- r is the grid electricity rate.
- e is the groundwater grid electricity.
- s is the share of grid electricity in the energy required to pump groundwater.
- g is the energy required to pump groundwater.
- gw is the volume of groundwater pumped.
- h is the total dynamic head.
- u is the overall pumping plant efficiency.
- k is the amount of energy required to lift one acre-foot of water one foot.[4]

Equations [1] and [2] rely on Equation [3], and these three expressions underlie the estimates of groundwater grid electricity use and its cost, both developed in this study and implemented in the model. Since the main driver for groundwater energy consumption is groundwater extraction, the model is organized according to the 56 planning areas (PA) used by the California Department of Water Resources (DWR) in its analyses for the state's water plans. In addition, in order to inform electric utilities in the state about future electric grid demand to

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[3] Chapter 2 of APPENDIX A describes several studies that estimated energy use for groundwater pumping. Namely, the chapter summarizes the work developed by Cervinka et al (1975), Hurr and Litke (1989), Wilkinson (2000), Cohen, Nelson, and Wolff (2004), Wilkinson et al (2006), Anderson (1999), Goldstein and Smith (2002), Pabi et al (2013), Burt, Howes, and Wilson (2003), and Park et al., (2010).

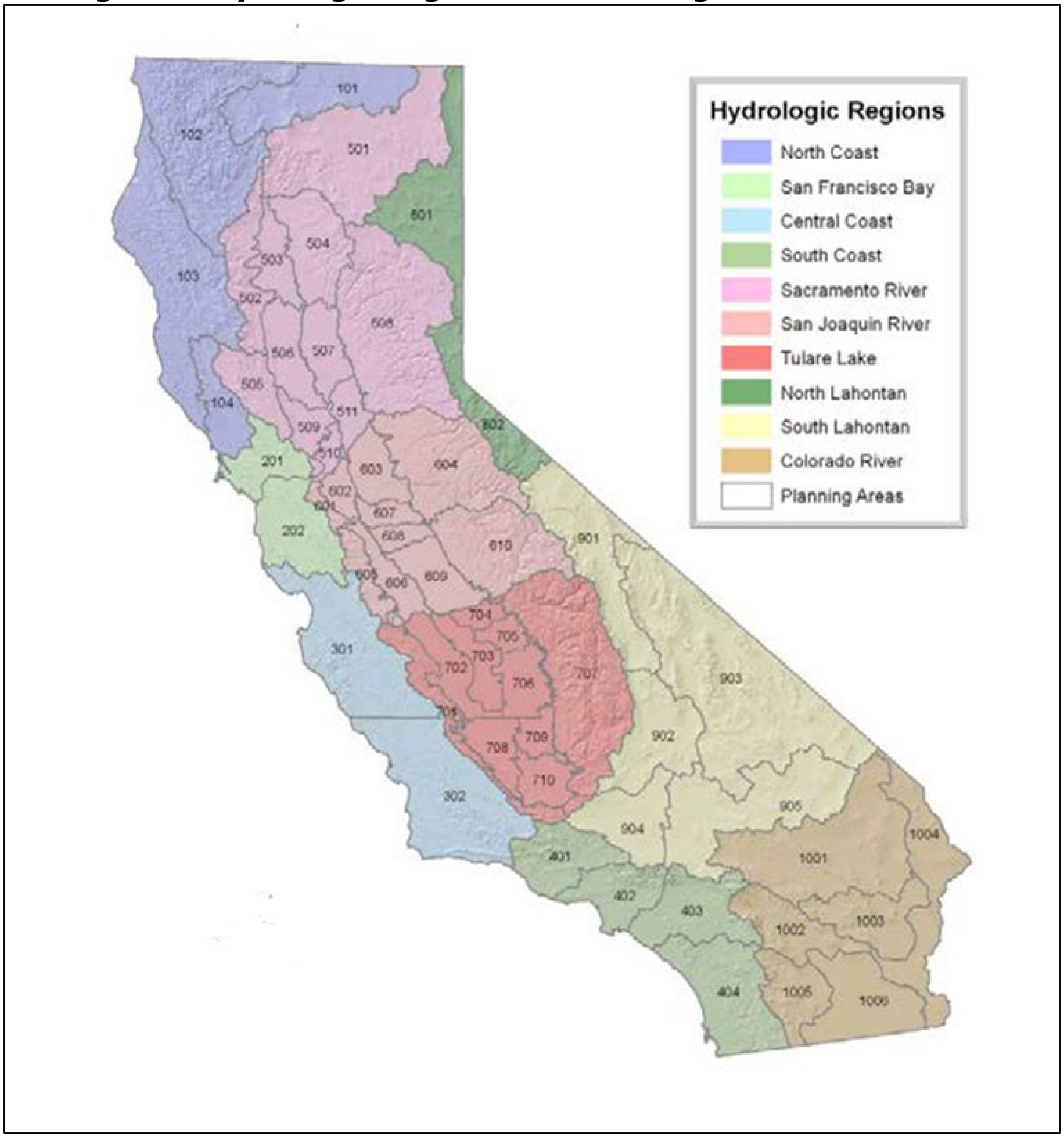
[4] The constant k is equal to 1.024 kilowatt-hours (kWh) per acre-foot (af) per foot (ft).

fuel groundwater pumping in the near term, results from the model were also shared with electric utilities.

Equations [1], [2], and [3] were evaluated for each of these PAs.

Figure 1 shows California's 10 hydrologic regions and 56 planning areas. The planning units are the numbered areas within the larger, colored hydrologic regions.

Figure 1: Hydrologic Regions and Planning Areas in California



Source: GEI Consultants/Navigant Consulting, Inc., 2010

2.1: Conceptual Data Analytical Framework

Hydrological conditions, population, economic activity (particularly water-intensive agriculture), the dynamics of groundwater levels, trends in pumping efficiency, use of grid electricity to pump groundwater, and grid electricity rates are all time-varying factors that affect the amount and cost of the grid electricity required to pump groundwater. They further differ across PAs. To determine the grid electricity use and its cost to pump groundwater in each PA, it is critical to understand those drivers, how they change over time, and how they relate to each other in each PA. To support this analysis, the study relies on a conceptual data analytical framework that underlies the relationships between those factors. Figure 2 shows this conceptual data analytical framework. The boxes represent the main data classes, and the solid arrows show causal relationships of influence. Dashed arrow lines show the influence of climatic and hydrological conditions on water requirements and supplies.

Overall, the data classes in the framework shown in Figure 2 represent the key factors associated with grid electricity use and cost as they relate to pumping groundwater. Population and urban landscape areas determine municipal water requirements. Irrigated acreage and water by crop, as well as climatic conditions, together make up estimates for agriculture water requirements. Water supply for industrial, commercial, energy, and environmental purposes complement the water requirement estimates. Surface water availability, subject to hydrological conditions and water reclamation practices, determine the volume of groundwater required. The volume of groundwater pumped also affects groundwater levels. Groundwater level data, combined with assumptions about drawdown and friction losses, together define total dynamic head (TDH);[5] TDH, in conjunction with volume of groundwater pumped and pumping efficiency, in turn determine groundwater energy requirements. Groundwater energy combined with the share of grid electricity used in groundwater pumping defines grid electricity requirements. Finally, grid electricity requirements and electricity rates determine electricity costs for groundwater pumping.

This analytical framework is the backbone of the analysis performed in this study. The framework guided the team's data collection, and also underlay development of the empirical relationships between the data classes represented in the framework. It also informed the development of the model developed for this research project.

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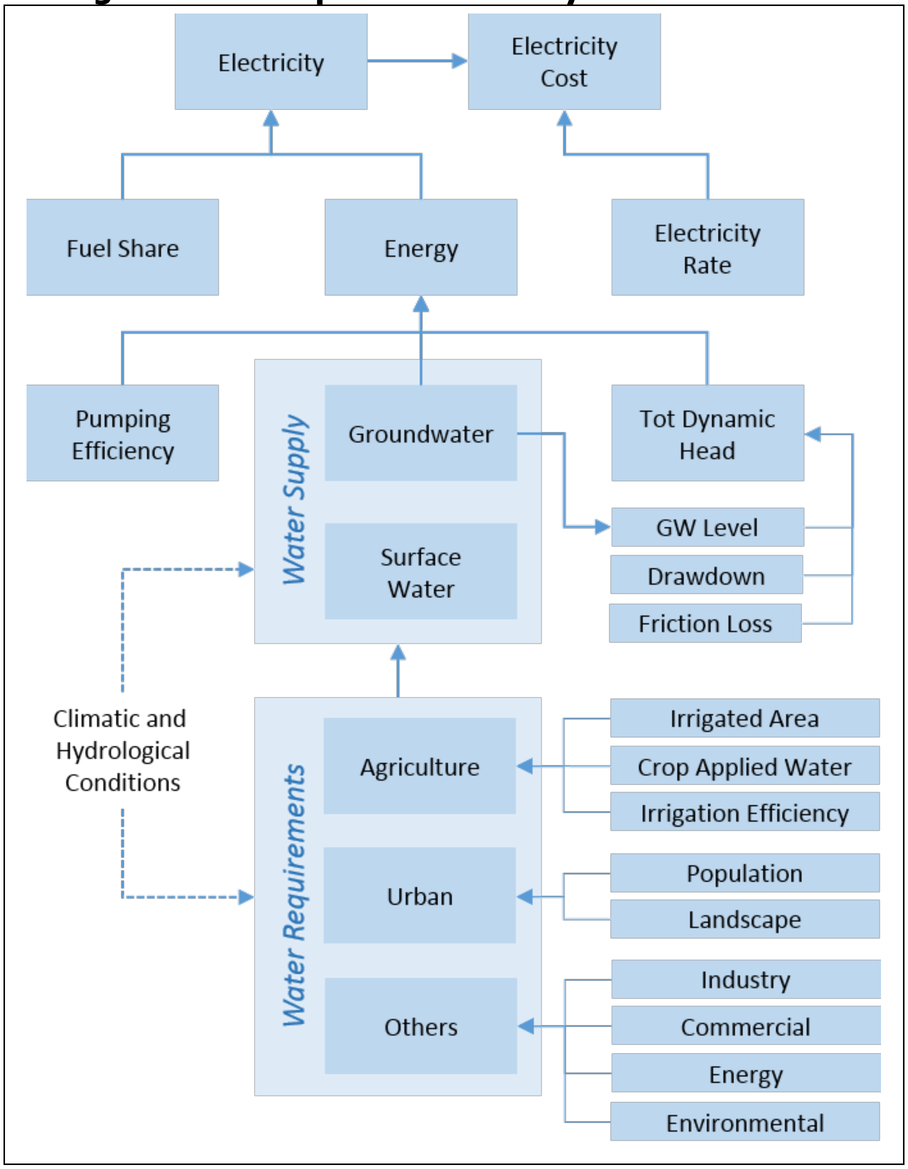
[5] This study focuses on the energy required only to pump (lift) groundwater. Therefore, the effect of discharge pressure on TDH is not accounted for here. The assumption of zero discharge pressure does not underestimate the importance of the energy required to pressurize the groundwater extracted for its application. Rather, it recognizes that the pressurization would be needed even if the water was supplied from a surface source, and consequently the energy burden from pressurizing the water should not be attributed to the fact the water is being supplied from groundwater.

Figure 2: Conceptual Data Analytical Framework

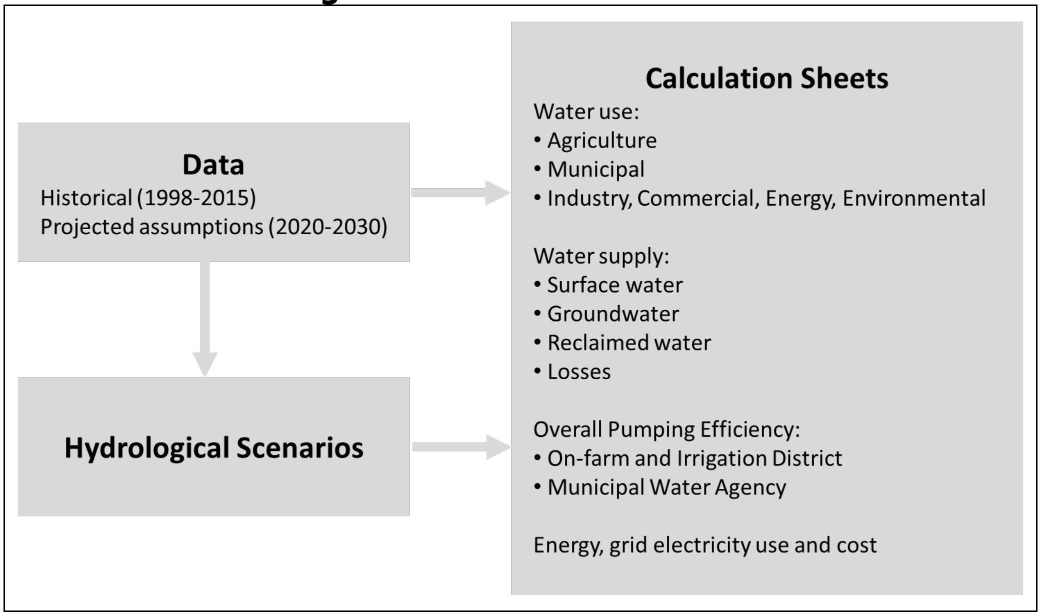


Source: GEI Consultants/Navigant Consulting, Inc., 2010

2.2: Model Architecture

The model is comprised of three components (Figure 3). The first component refers to the data used by the model, including historical (1998-2015) and projected (2020-2030) values of the relevant variables (represented by the data classes in Figure 2). The second component addresses future climatic and hydrological conditions. A critical factor that determines water supply (and sometimes its use) is the annual hydrological condition for which annual groundwater energy consumption is estimated. The model relies on climatic and hydrological characteristics of recent years to estimate annual water supply for the projected period of 2020-2030. The climatic and hydrological characteristics of recent years were used to synthesize three sets of 100 climatic scenarios, each comprised of an 11-year sequence of years randomly sampled from a set of years within the historical data used in this study.

Figure 3: Model Architecture



Source: GEI Consultants/Navigant Consulting, Inc., 2010

The third component of the model is the set of calculation sheets that combine the values of relevant variables for each PA to calculate historical and future grid electricity requirements and costs for groundwater pumping. Calculations were made from water use to water supply; from water supply, TDH, and pumping efficiency to energy requirements; and from energy requirements to grid electricity use and its cost.

For purposes of estimating groundwater energy in recent years, the model used historical data of groundwater extraction to calculate groundwater energy for each PA. Since groundwater is extracted by different pumpers with different pumping efficiencies, the model disaggregates the total amount of groundwater pumped across four types of pumpers: farmers, irrigation districts, municipal suppliers, and pumpers that pump groundwater for environmental applications:

$$gw = gwFarm + gwID + gwMun + gwEnv \qquad [4]$$

where:

gw	is the total volume of groundwater extracted (in thousand acre-feet).
$gwFarm$	is the groundwater pumped on farm (in thousand acre-feet).
$gwID$	is the groundwater pumped by irrigation districts (in thousand acre-feet).
$gwMun$	is the groundwater pumped by municipal suppliers (in thousand acre-feet).
$gwEnv$	is the groundwater pumped for environmental applications (in thousand acre-feet).

To project groundwater extraction in each PA, the model used the balance of total water required and supplied (Equation [5a]) on the disaggregation of the total supply across water sources (Equation [5b]):

$$wSup = wReq + wLoss \quad [5a]$$

$$gw = wSup - wSurf - wRec = (wReq + wLoss) - wSurf - wRec \quad [5b]$$

where:

$wSup$	is the total volume of water supplied (in thousand acre-feet).
$wReq$	is the total volume of water required (in thousand acre-feet).
$wLoss$	is the volume of water lost in the conveyance process (in thousand acre-feet).
gw	is the volume supplied from groundwater (in thousand acre-feet).
$wSurf$	is the volume supplied from surface water (in thousand acre-feet).
$wRec$	is the volume supplied from reclaimed water (in thousand acre-feet).

To estimate total water requirements ($wReq$) in Equation [5b], the volume of total water required is disaggregated into water used for agricultural, municipal, and other (industrial, commercial, energy, and environmental) applications. Municipal water use is further broken out into indoor and outdoor (landscape) use. Estimates of water use are based on the following equations:

$$wReq = wAgr + (wMunIn + wMunOut) + wOth \quad [6]$$

where:

$$wAgr = lAgr.zAgr. \quad [6a]$$

$$wMunIn = p.zMunIn. \quad [6b]$$

$$wMunOut = lMun.zMunOut. \quad [6c]$$

$$wOth = wInd + wCom + wEnr + wEnv. \quad [6d]$$

and:

$wAgr$	is the agriculture irrigation applied water (in thousand acre-feet).
$lAgr$	is the irrigated crop area (in thousand acres).
$zAgr$	is the per-acre crop irrigation applied water (in feet).
$wMunIn$	is the municipal indoor water use (in thousand acre-feet).
p	is the population (in thousand inhabitants).
$zMunIn$	is the per capita indoor water use (in acre-feet per thousand inhabitants).
$wMunOut$	is the municipal outdoor applied water (in thousand acre-feet).
$lMun$	is the irrigated landscape area (in thousand acres).
$zMunOut$	is the per-acre landscape irrigation applied water use (in feet).
$wOth$	is the total volume of water for other applications (in thousand acre-feet).
$wInd$	is the volume of water for industrial application (in thousand acre-feet).

$wCom$ is the volume of water for commercial application (in thousand acre-feet).

$wEnr$ is the volume of water used for energy (in thousand acre-feet).

$wEnv$ is the volume of water used for environmental applications (in thousand acre-feet).

Water requirements for other than agricultural and municipal applications were determined at the level of each PA, according to the characteristics of each use in recent years. These water uses were projected—sometimes following a temporal trend, sometimes as historical means, and are sometimes associated with the hydrological conditions of the year sampled. Equation [6] supports estimates of groundwater extraction as defined in Equation [5b]. Projections of the other components of Equation [5b] are explained in the following chapters. Once the amount of groundwater extracted is estimated for each PA, based on Equation [5b], the grid electricity use and costs are calculated from equations [1]-[3]. Data and assumptions that underlie projections of the other components of the latter equations are described in Chapter 3 and Chapter 4.

CHAPTER 3: Data and Assumptions

3.1: Water Use and Supply

Water use is based on water-balance historical data (1998-2015) provided by the California Department of Water Resources (DWR). Projections of water use are disaggregated into agricultural, municipal, and other applications, as described in Equation [6]. To project agricultural water use (Equation [6a]), the team projected irrigated crop area at the PA level based on potential trends and relationships that irrigated crop area may have with the hydrological conditions of the year. The research team also projected crop irrigation water consumption where irrigation efficiency increases over time, based on two alternative assumptions described in Chapter 4.

Indoor and outdoor municipal water use was additionally estimated. For indoor use (Equation [6b]), the team projected annual population for the 2020-2030 period at the PA level. The team further projected per-capita indoor water use for two scenarios, where the use declines over time based on two alternative assumptions (described in Chapter 4). As for outdoor application (landscape irrigation) (Equation [6c]), the team projected annual water requirements according to the hydrological conditions estimated for each year and under the assumption that urban irrigated landscape area is proportional to population. Further, to support the estimate of water required for landscape irrigation, the team projected landscape water intensity for two scenarios (described in Chapter 4), where intensity is estimated to decline at different rates for old and new landscape areas. Projections of industrial, commercial, energy, and environmental water use are specific for each PA, and rely on historical data of these uses in the given PA.

Water supply is also based on water balance historical data (1998-2015) provided by DWR. Total water supply is calculated, for each PA, to meet the total water requirements plus losses (Equation [5a]). Surface water is projected under the assumption that the amount of surface water available is the same as in the historical year that defines the hydrological conditions of the projected year. Supply from reclaimed water is projected according to characteristics of that source of supply in each PA. Once supply from these two sources are estimated, groundwater extraction is projected according to Equation [5b]. The projected groundwater extraction is then disaggregated based on the following assumptions. First, the shares of groundwater extraction across the three applications of groundwater—agriculture, municipal, and environmental—are projected to be the same as in the historical year that defines the hydrological conditions of the projected year. Then, in the particular case of groundwater pumped for agricultural application, the estimated total groundwater extraction is disaggregated into on-farm groundwater extraction and groundwater pumped by irrigation districts. The latter disaggregation assumes that the share of groundwater pumped by districts, relative to total groundwater extracted for agricultural use, follows the same share as the total water deliveries by districts relative to total agricultural water use. This allows for estimating groundwater extraction by irrigation districts in the PA. On-farm groundwater extraction is then calculated as the difference of total groundwater pumped for agriculture and the volume of groundwater pumped by districts.

3.2: Total Dynamic Head and Pumping Efficiency

Total dynamic head (TDH), which is the total equivalent height that groundwater is pumped (taking into account the additional energy required from drawdown and friction loss effects),[6] was projected from both earlier team estimates (APPENDIX A, Chapter 6) and assumptions the team further developed to project the dynamics of groundwater levels. Groundwater level changes were projected based on the hydrological conditions and groundwater extracted in the historical year that defined the hydrological conditions of the projected year. The team relied on the Sacramento Valley Water Year Classification Index (Water Index),[7] provided by DWR, to classify each year in the set of years represented in the historical data used in this study. The Water Index classifies the hydrological conditions of a water year as: *wet*, *above normal*, *below normal*, *dry*, and *critical*. Based on these five categories, the team developed a transition matrix that estimated expected changes in groundwater levels for each possible transition across the five categories.[8] The changes in groundwater level were then used to dynamically project groundwater static levels according to hydrological estimates for both the projected and previous years.

Overall pumping plant efficiency (OPPE), the relationship between a certain amount of groundwater pumped from a given TDH and the power consumed to pump it, was projected based on values the team previously estimated (APPENDIX A, Chapter 6) and on assumptions about improvements in pumping efficiency, described in Chapter 4.

3.3: Pumping Fuels and Electricity Rates

The team projected well-pump fuels based on the following assumptions. The team assumed that all well pumps operated by water suppliers, both agricultural and municipal, were electric. For on-farm groundwater pumping, the team relied on survey data provided by the U.S. Department of Agriculture and the National Agricultural Statistics Survey's Farm and Ranch Irrigation surveys (FRIS), conducted in 2002, 2007, and 2012. The surveys show an upward trend in the share of electric pumps when compared with the share of non-electric pumps. The team in turn relied on that trend to project the share of electric well pumps for 2020-2030. In addition, surveys showed an increasing trend in the percentage of on-farm well pumps fueled by solar photovoltaics (PV) or other renewable resources.[9] The team relied on that trend to project the share of on-farm well pumps fueled by on-farm-generated electricity. Based on

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[6] The other component of TDH is discharge pressure. Discharge pressure is not being accounted for in this study. Please refer to footnote 5 for details.

[7] DWR, Water Year Hydrologic Classification Indices. http://cdec.water.ca.gov/reportapp/javareports?name=WSIHIST.

[8] For example, transitioning from a wet year to a dry year; from an above normal year to a wet year; or from a below normal year to a critical year.

[9] In a survey described in another report of this project ("Barriers to Energy and Water Efficiency and Conservation Practices in Groundwater Pumping"), growers also indicated a tendency to shift towards on-farm solar PV powered well pumps.

these data and assumptions, grid electricity requirements were projected according to equations [2]-[3].

Electricity rates are from DOE's Energy Information Administration (EIA). The team previously estimated annual average electricity rates for groundwater pumping from historical data (1997-2015) on monthly commercial electricity rates, adjusted to 2018's dollar value for the 1998-2015 water years. Projections of electricity rates are based on EIA projections of commercial electricity price trends for three scenarios of economic growth: reference growth, low economic growth, and high economic growth (described in Chapter 4).

CHAPTER 4: Grid Electricity Use and Costs

The research team's model estimated grid electricity use and costs for two periods. First, the team estimated these requirements and costs for 2005-2015 based on historical data and the assumptions just described. The team then developed three sets of 100 hydrological scenarios to support the projection of variables whose values are associated with the hydrological conditions of the year for which electricity use and costs are being estimated. Each hydrological scenario is comprised of a sequence of 11 years, randomly selected from water years 1998-2015 classified by the Water Index as *wet* (Wet scenario); *above normal* or *below normal* (Normal scenario); and *dry* or *critical* (Dry scenario). The team also defined other scenarios, where the relevant variables take different values according to alternative assumptions that underlie each scenario. Finally, the team combined the hydrological scenarios with the variable-specific scenarios to project annual electricity use and costs for 2020-2030.

4.1: Past Use and Costs (2005-2015)

The team estimates that a total of 58.8 TWh were used to pump groundwater in California from 2005 to 2015. Of that amount of energy, 51.7 TWh are estimated to have been powered by grid electricity, at a total cost of 6.4 billion 2018 dollars for groundwater pumpers. Table 1, Table 2, and Table 3 summarize these results by hydrological region (HR). Approximately 51.3 percent of the total energy was consumed in the Tulare Lake hydrological region. The San Joaquin River and Sacramento River hydrological regions represent, respectively, 17.4 percent and 10.1 percent of the total energy estimated to pump groundwater. The three hydrological regions consumed, respectively, 50.2 percent, 17.3 percent, and 10.3 percent of the total grid electricity used to pump groundwater in the state. Concerning pumping costs, groundwater pumpers in these three hydrological regions spent, respectively, 51.6 percent, 17.2 percent, and 9.9 percent of the total cost of grid electricity used to pump groundwater. To put that in perspective, the average annual grid electricity use and cost to pump groundwater in these three hydrological regions is 8.2 times the average electricity use and cost of all other regions.

Energy used to pump groundwater during the 2012-2015 drought period varied from 26.0 percent to 58.4 percent of the total energy used during the 2005-2015 period. Similarly, grid electricity used during the drought varied from 26.2 percent to 58.6 percent of the total grid electricity used during 2005-2015, with grid electricity pumping cost from 31.3 percent to 64.4 percent of the total grid electricity pumping cost for 2005-2015. When considering that six water years classified by the Water Index as either dry or critical during the 2005-2015 period,[10] the energy used to pump groundwater during these years varied from 48.5 percent to 72.6 percent. Grid electricity use and cost vary, respectively, from 48.4 percent to 72.5 percent, and from 51.5 percent to 75.6 percent of the total grid electricity use and cost during the 2005-2015 period.

[10] The years are between 2007-2009 and 2013-2015.

Table 1: Energy Used for Groundwater Pumping 2005-2015 (GWh)

Hydrologic Region	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Central Coast	201	166	291	265	261	205	225	283	362	388	354
Colorado River	188	154	154	141	150	124	124	165	92	107	66
North Coast	43	56	57	57	53	50	51	59	6 2	64	60
North Lahontan	25	29	32	31	33	32	15	16	18	19	17
South Coast	349	519	553	523	534	403	391	436	539	600	453
San Francisco	42	41	45	50	49	40	40	48	45	49	57
San Joaquin River	532	639	847	979	1015	706	651	909	1097	1344	1522
South Lahontan	102	110	134	129	125	109	93	103	135	148	104
Sacramento River	483	487	592	620	589	514	422	506	565	565	611
Tulare Lake	1090	914	1964	2495	2776	2090	1201	2977	4002	5288	5344

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Table 2: Grid Electricity Used for Groundwater Pumping 2005-2015 (GWh)

Hydrologic Region	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Central Coast	167	142	247	226	223	177	193	243	310	332	304
Colorado River	186	152	152	139	149	123	123	164	90	106	65
North Coast	38	48	50	50	47	44	45	52	55	57	53
North Lahontan	21	25	28	27	29	29	13	14	16	16	15
South Coast	340	497	523	496	507	383	372	417	510	566	429
San Francisco	41	39	43	47	47	39	38	46	43	47	54
San Joaquin River	463	553	734	854	889	626	573	794	963	1177	1327
South Lahontan	90	98	119	117	114	99	84	92	120	133	94
Sacramento River	426	433	529	557	530	466	380	455	509	507	548
Tulare Lake	920	781	1671	2142	2388	1810	1044	2589	3449	4573	4619

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Table 3: Grid Electricity Cost of Groundwater Pumping 2005-2015 (million 2018$)

Hydrologic Region	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Central Coast	14.5	14.1	25.7	24.1	26.2	20.6	22.8	29.4	40.3	47.9	46.6
Colorado River	16.2	15.2	15.8	14.8	17.5	14.3	14.5	19.8	11.7	15.2	9.9
North Coast	3.3	4.8	5.2	5.3	5.5	5.2	5.3	6.3	7.2	8.2	8.1
North Lahontan	1.9	2.5	2.9	2.9	3.5	3.3	1.5	1.7	2.1	2.4	2.2
South Coast	29.5	49.7	54.5	52.8	59.6	44.5	44.0	50.4	66.3	81.6	65.9
San Francisco	3.5	3.9	4.4	5.1	5.5	4.5	4.5	5.6	5.6	6.8	8.3
San Joaquin River	40.3	55.2	76.5	91.0	104.5	72.8	67.9	96.0	125.2	169.7	203.7
South Lahontan	7.8	9.8	12.4	12.5	13.3	11.5	9.9	11.1	15.6	19.1	14.4
Sacramento River	37.0	43.3	55.1	59.3	62.3	54.2	45.0	55.0	66.2	73.1	84.1
Tulare Lake	79.9	78.0	174.1	228.1	280.7	210.5	123.7	313.1	448.4	659.3	708.9

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Between 2005 and 2015, 19 PAs used a total amount of energy to pump groundwater greater than 1,000 GWh (for each PA). Together, the energy these PAs used represents 86.1 percent of the total energy used to pump groundwater. Table 4 lists these PAs, with their corresponding 2005-2015 cumulative groundwater energy and grid electricity use and cost. The energy used in each of these PAs to pump groundwater during the six dry and critical years in the 2005-2015 period varied from 46.8 percent to 78.2 percent of their cumulative energy used to pump groundwater. The cost of grid electricity to pump groundwater in the dry and critical years varies from 49.8 percent to 81.2 percent of what groundwater pumpers in these PAs were estimated to have spent with grid electricity to pump groundwater.

In addition to estimating total energy, grid electricity use, and cost for groundwater pumping at the PA level, the team relied on GIS software to map the geographical locations of PAs in their respective electric utility service territories. Based on this mapping, and under the assumption of spatially uniformly distributed population and crop land within each PA, the team estimated groundwater energy and grid electricity use and costs for each electric utility. The team then aggregated the results by utility into six areas: the service territories of Pacific Gas & Electric (PG&E), Southern California Edison (SCE), San Diego Gas & Electric (SDG&E), and other utilities in northern, central, and southern California. Table 5 summarizes the total grid electricity used to pump groundwater in each of these areas. The electricity used by PG&E and SCE customers to pump groundwater corresponds, respectively, to 63.8 percent and 23.9 percent of the total grid electricity used to pump ground water in the state.

Table 4: Energy and Grid Electricity Use and Costs 2005-2015 by PA

Hydrologic Region and Planning Area			Energy (GWh)	Grid Electricity Use (GWh)	Grid Electricity Cost (mi 2018$)
CC	301	Northern	1556	1333	161.4
CC	302	Southern	1445	1231	150.9
SC	401	Santa Clara	1067	922	113.2
SC	402	Metro LA	1500	1499	177.1
SC	403	Santa Ana	2555	2454	289.4
SR	506	Colusa Basin	1362	1202	142.6
SR	509	Central Basin West	1057	967	114.1
SJ	603	Eastern Valley Floor	1593	1342	163.9
SJ	606	Valley West Side	2755	2496	305.8
SJ	608	Middle Valley East Side	1121	1001	122.8
SJ	609	Lower Valley East Side	3987	3374	419.7
TL	702	San Luis W Side	3617	3231	425.4
TL	703	Lower Kings-Tulare	5869	4933	612.5
TL	705	Alta-Orange Cove	1336	1131	142.6
TL	706	Kaweah Delta	7513	6424	805.8
TL	708	Semitropic	2773	2388	311.9
TL	709	Kern Valley Floor	4360	3767	484.9
TL	710	Kern Delta	3939	3417	435.5
CR	1002	Coachella	1212	1207	136.4

Legend: CC, Central Coast; SC, South Coast; SR, Sacramento River; SJ, San Joaquin River; TL, Tulare Lake; CR, Colorado River

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Table 5: Grid Electricity Used for Groundwater Pumping 2005-2015 (GWh)

Electric Utility	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
PG&E	1574	1499	2370	2810	3054	2383	1813	3167	4105	5000	5229
SCE	664	787	1140	1236	1239	906	645	1123	1324	1758	1543
SDGE	16	14	14	14	14	14	13	12	13	13	11
Northern CA	70	72	99	106	112	99	60	103	125	155	154
Central CA	30	41	53	62	64	42	36	46	63	82	89
Southern CA	338	355	421	429	441	351	298	414	435	505	480

Source: GEI Consultants/Navigant Consulting, Inc., 2010

4.2: Projected Use and Costs (2020-2030)

The team projected groundwater grid electricity use and cost for 2020-2030 based on both data and assumptions described in Chapter 3 and the hydrological scenarios just described. Agricultural water use in each PA is driven by the irrigated crop area and per-acre applied water. It is also affected by how efficiently the per-acre applied water irrigates crops. The team projected irrigated crop area and per-acre applied water in each PA according to both temporal trends and the hydrological conditions of the year observed, from 1998 to 2015 (APPENDIX A, Chapter 5). As for irrigation efficiency, for its baseline scenario the team used previously estimated trends (APPENDIX A, Chapter 5). In an alternative scenario, the team assumed that crop irrigation efficiency in each PA would reach, in 2030, best practice across all PAs in the hydrological region, which is the highest crop irrigation efficiency the model projects for a given hydrological region in 2030.

In the case of municipal indoor and outdoor water use, the team projected groundwater grid electricity use and cost based on the following alternative assumptions:

- **Indoor Water Use:** Indoor water use is driven by population and per capita water use. In its baseline projection, the team assumed that population follows estimates provided by DWR (based on estimates developed by the California Department of Finance), and that per-capita indoor water use meets key goals: 55 gallons per capita per day (GPCD) in 2020, 52 GPCD in 2025, and 50 GPCD in 2030. In an alternative scenario, the team relied on its own projections of population and GPCD (by PA), which follow corresponding trends observed from 1998 to 2015 (APPENDIX A, Chapter 5).
- **Outdoor Water Use:** Outdoor water use is driven by landscaped area, which in this model is driven by hydrological conditions, population, and landscape water intensity. In its baseline projection, landscape area relies on the baseline assumption for population. Concerning landscape water intensity, the team assumed in its baseline projection that all new landscape area (the landscape area added on or after 2020) will be irrigated at the rate of 50 percent of the reference evapotranspiration (ET_0), and the old landscape area (the landscape area that existed before 2020) will be irrigated with a declining rate of 100 percent of ET_0 in 2020 to 70 percent of ET_0 in 2030. In an alternative scenario, the team assumed that in 2030 the old landscape area will be irrigated at the same rate as the new landscape areas (50 percent of ET_0).

The team also developed alternative assumptions for OPPE for its projections of groundwater grid electricity use and cost for 2020-2030. In its baseline scenario, the team assumed no significant improvements will happen in OPPE; the team assumed previously estimated values will remain in place (APPENDIX A, Chapter 6). In an alternative scenario, the team assumed that OPPE in each PA, and for each type of groundwater pumper, will reach, in 2030, the current best practice across all PAs, which is the lowest OPPE the team estimated for each PA.

Concerning the share of grid electricity in groundwater pumping energy, the team relied on two alternative assumptions to project that share in 2020-2030. In its baseline scenario, the team assumed that the share of on-farm electric well pumps and the share of on-farm well pumps powered by solar or other renewable resources will grow according to the trends the team developed (APPENDIX A, Chapter 6). In an alternative scenario, the team assumed an aggressive increase in penetration of on-farm electric well pumps and solar/other renewable powered well pumps. The team assumed that in 2030 all on-farm well pumps will be electric, and that 10 percent of those pumps will be powered by solar or other renewable energy sources.

Electricity rates were projected under three assumptions that reflect the uncertainty of economic growth and the impacts of that growth on the energy market. In its baseline projection, the team used EIA's 2019 Annual Energy Outlook (AEO) Reference Case scenario, where population grows by an average of 0.5 percent per year, nonfarm employment grows by 0.6 percent, and productivity grows by 1.5 percent from 2018 to 2050; gross domestic product (GDP) increases by 1.9 percent per year from 2018 to 2050, and growth in real disposable income per capita averages 2.1 percent per year. For its alternative scenarios, the team used AEO's low- and high economic growth cases. The Low Economic Growth Case assumes an average annual population growth rate of 0.4 percent and a nonfarm employment rate of 0.4 percent; GDP increases by 1.4 percent per year from 2018 through 2050, and growth in real disposable income per capita averages 1.9 percent per year. The High Economic Growth case assumes an average annual population growth rate of 0.7 percent and nonfarm employment of 0.8 percent per year. GDP grows at the rate of 2.4 percent per year, and real disposable income per capita grows by 2.5 percent per year. Table 6 summarizes these scenarios.

Table 6: Baseline and Alternative Scenarios

Scenario	**Baseline (assumption)**	**Alternative (assumption)**
Population	CA DoF	Trends from historical data
GPCD	CA goals (2020, 2025, 2030)	Trends from historical data
Landscape	2030: Old landscape 70% ET_0	2030: Old landscape 50% ET_0
Irrigation Efficiency	Trends from historical data	Best practice in the HR
OPPE	No improvement	Best practice in the HR
Electrification	Trends from historical data	2030: All electric 2030: 10% solar/renewables
Low Growth	Reference growth	Low economic growth
High Growth	Reference growth	High economic growth

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Table 7 to Table 16 summarize total energy, grid electricity, and grid electricity costs for groundwater pumping in the 2020-2030 period in each of the 10 hydrological regions. These tables refer to both baseline and alternative scenarios. Minimum, average, and maximum values also appear for each hydrological scenario. The three hydrological regions where most of the energy is consumed are Tulare Lake, San Joaquin River, and Sacramento River. These three hydrologic regions comprise the Central Valley, an agriculturally intensive region.[11] In normal hydrological years, the region is projected to use an annual average of 6.8 TWh of grid electricity, while the rest of the state is projected to use 2.0 TWh. In drier years, the region is projected to use an annual average of 9.0 TWh of grid electricity, and the rest of the state 2.9 TWh. Because groundwater use during dry periods is projected to increase in the rest of the state proportionately faster than the increase in the three hydrological regions, the share of groundwater grid electricity in the Central Valley declines from 78 percent to 76 percent when the electricity used during normal hydrological years is compared with drier years. The hydrological region that is most sensitive to hydrological conditions is North Coast, followed by Tulare Lake, North Lahontan, South Lahontan, and South Coast. The total projected cost of grid electricity for groundwater pumping is $15.6 billion under normal hydrological conditions. This cost drops to $13.2 billion in the wet scenario and increases to $21.3 billion in the dry scenario. one. Lower/higher economic growth may decrease/increase these costs by about 1 percent.

The scenario with the largest impact in groundwater energy use is irrigation efficiency, which demonstrates that agriculture should be a primary target for reducing groundwater energy. The hydrological region with the largest opportunity to reduce electricity for groundwater pumping by increasing irrigation efficiency is Colorado River, followed by San Joaquin River, Tulare Lake, and South Coast. Reducing the GPCD in South Lahontan, and improving OPPE in the Sacramento River, South Lahontan, South Coast, and San Francisco hydrological regions can also reduce educing groundwater energy use. Transitioning to all-electric well pumps, while increasing the penetration of pumps powered by solar or other renewables, would also increase grid electricity use over the projected period by 1.5 percent.

The team then apportioned projected grid electricity consumption required by the state's respective utility service territories. Table 17 and Table 18 present these results. PG&E, SCE, and SDG&E, California's three large investor-owned utilities, are most impacted by these scenarios so also have the most to gain from improving irrigation efficiency.

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[11] Agriculture is the largest consumer of groundwater in the state.

Table 7: Energy and Grid Electricity Use and Costs 2020-2030 (Central Coast)

Scenario	Hydrological Scenario Wet			Hydrological Scenario Normal			Hydrological Scenario Dry		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Energy (TWh)									
Baseline	6.2	6.4	6.5	6.6	6.7	7.0	7.9	8.0	8.2
Population	6.2	6.4	6.5	6.6	6.8	7.0	7.9	8.0	8.2
GPCD	6.1	6.3	6.4	6.5	6.6	6.9	7.8	7.9	8.1
Landscape	6.2	6.4	6.5	6.6	6.7	7.0	7.9	8.0	8.2
Irrigation Efficiency	5.9	6.2	6.3	6.3	6.5	6.7	7.6	7.7	7.9
OPPE	6.1	6.4	6.5	6.5	6.7	7.0	7.9	8.0	8.2
Electrification	6.2	6.4	6.5	6.6	6.7	7.0	7.9	8.0	8.2
Grid Electricity (TWh)									
Baseline	5.4	5.6	5.7	5.8	5.9	6.1	6.9	7.0	7.1
Population	5.4	5.6	5.7	5.8	5.9	6.1	6.9	7.0	7.2
GPCD	5.3	5.5	5.6	5.7	5.8	6.0	6.8	6.9	7.0
Landscape	5.4	5.6	5.7	5.8	5.9	6.1	6.9	7.0	7.1
Irrigation Efficiency	5.2	5.4	5.5	5.5	5.7	5.9	6.6	6.8	6.9
OPPE	5.4	5.6	5.7	5.7	5.9	6.1	6.9	7.0	7.1
Electrification	5.5	5.7	5.8	5.9	6.1	6.3	7.1	7.2	7.3
Grid Electricity (billion $2018)									
Baseline	0.88	0.91	0.92	0.93	1.0	1.0	1.1	1.1	1.2
Low Growth	0.87	0.90	0.92	0.93	1.0	1.0	1.1	1.1	1.2
High Growth	0.89	0.92	0.93	0.94	1.0	1.0	1.1	1.2	1.2

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Table 8: Energy and Grid Electricity Use and Costs 2020-2030 (Colorado River)

Scenario	Hydrological Scenario Wet			Hydrological Scenario Normal			Hydrological Scenario Dry		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Energy (TWh)									
Baseline	10.6	10.8	11.1	11.6	12.2	12.7	14.0	14.4	14.7
Population	10.5	10.8	11.1	11.5	12.1	12.7	13.9	14.3	14.6
GPCD	10.3	10.5	10.8	11.2	11.9	12.4	13.6	14.0	14.3
Landscape	10.6	10.8	11.1	11.6	12.2	12.7	14.0	14.4	14.7
Irrigation Efficiency	7.9	8.1	8.3	8.7	9.1	9.5	10.3	10.6	10.8
OPPE	10.4	10.7	11.0	11.4	12.0	12.5	13.8	14.2	14.5
Electrification	10.6	10.8	11.1	11.6	12.2	12.7	14.0	14.4	14.7
Grid Electricity (TWh)									
Baseline	10.5	10.8	11.1	11.5	12.1	12.7	13.9	14.3	14.6
Population	10.5	10.7	11.0	11.5	12.1	12.6	13.8	14.2	14.6
GPCD	10.2	10.5	10.7	11.2	11.8	12.3	13.5	13.9	14.2
Landscape	10.5	10.8	11.1	11.5	12.1	12.6	13.9	14.3	14.6
Irrigation Efficiency	7.9	8.1	8.3	8.6	9.1	9.4	10.2	10.5	10.8
OPPE	10.4	10.6	10.9	11.4	12.0	12.5	13.7	14.1	14.4
Electrification	10.5	10.8	11.1	11.5	12.1	12.7	13.9	14.3	14.6
Grid Electricity (billion $2018)									
Baseline	1.7	1.8	1.8	1.9	2.0	2.1	2.3	2.3	2.4
Low Growth	1.7	1.7	1.8	1.9	2.0	2.0	2.3	2.3	2.4
High Growth	1.7	1.8	1.8	1.9	2.0	2.1	2.3	2.4	2.4

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Table 9: Energy and Grid Electricity Use and Costs 2020-2030 (North Coast)

Scenario	Hydrological Scenario Wet			Hydrological Scenario Normal			Hydrological Scenario Dry		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Energy (TWh)									
Baseline	0.05	0.11	0.21	0.58	1.0	1.3	4.7	7.9	9.4
Population	0.05	0.11	0.21	0.58	1.0	1.3	4.7	7.9	9.4
GPCD	0.05	0.11	0.22	0.58	1.0	1.3	4.7	7.9	9.4
Landscape	0.05	0.11	0.21	0.58	1.0	1.3	4.7	7.9	9.4
Irrigation Efficiency	0.05	0.11	0.22	0.58	1.0	1.3	4.7	7.9	9.4
OPPE	0.05	0.11	0.21	0.57	0.98	1.3	4.6	7.8	9.3
Electrification	0.05	0.11	0.21	0.58	1.0	1.3	4.7	7.9	9.4
Grid Electricity (TWh)									
Baseline	0.04	0.10	0.19	0.54	0.93	1.3	4.3	7.4	8.8
Population	0.04	0.10	0.19	0.54	0.93	1.3	4.3	7.4	8.8
GPCD	0.05	0.10	0.20	0.54	0.93	1.3	4.3	7.4	8.8
Landscape	0.04	0.10	0.19	0.54	0.93	1.3	4.3	7.4	8.8
Irrigation Efficiency	0.05	0.10	0.20	0.54	0.93	1.3	4.3	7.4	8.8
OPPE	0.04	0.10	0.19	0.53	0.92	1.3	4.3	7.3	8.7
Electrification	0.04	0.10	0.19	0.55	0.94	1.3	4.4	7.4	8.8
Grid Electricity (billion $2018)									
Baseline	0.01	0.02	0.03	0.09	0.15	0.21	0.70	1.2	1.4
Low Growth	0.01	0.02	0.03	0.09	0.15	0.21	0.70	1.2	1.4
High Growth	0.01	0.02	0.03	0.09	0.15	0.21	0.71	1.2	1.4

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Table 10: Energy and Grid Electricity Use and Costs 2020-2030 (North Lahontan)

Scenario	Hydrological Scenario Wet			Hydrological Scenario Normal			Hydrological Scenario Dry		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Energy (TWh)									
Baseline	0.23	0.26	0.30	0.30	0.34	0.37	0.37	0.41	0.48
Population	0.23	0.26	0.30	0.30	0.34	0.37	0.37	0.41	0.48
GPCD	0.25	0.28	0.32	0.33	0.36	0.39	0.39	0.43	0.51
Landscape	0.23	0.26	0.30	0.30	0.34	0.37	0.37	0.41	0.48
Irrigation Efficiency	0.23	0.26	0.30	0.30	0.34	0.37	0.37	0.41	0.48
OPPE	0.23	0.26	0.30	0.30	0.34	0.37	0.37	0.41	0.48
Electrification	0.23	0.26	0.30	0.30	0.34	0.37	0.37	0.41	0.48
Grid Electricity (TWh)									
Baseline	0.20	0.23	0.27	0.27	0.31	0.33	0.34	0.38	0.45
Population	0.20	0.23	0.27	0.27	0.31	0.33	0.34	0.38	0.45
GPCD	0.22	0.25	0.29	0.29	0.33	0.35	0.36	0.40	0.47
Landscape	0.20	0.23	0.27	0.27	0.31	0.33	0.34	0.38	0.45
Irrigation Efficiency	0.20	0.23	0.27	0.27	0.31	0.33	0.34	0.38	0.45
OPPE	0.20	0.23	0.27	0.27	0.31	0.33	0.34	0.38	0.45
Electrification	0.21	0.24	0.27	0.28	0.31	0.34	0.34	0.38	0.45
Grid Electricity (billion $2018)									
Baseline	0.03	0.04	0.04	0.04	0.05	0.05	0.05	0.06	0.07
Low Growth	0.03	0.04	0.04	0.04	0.05	0.05	0.05	0.06	0.07
High Growth	0.03	0.04	0.04	0.04	0.05	0.05	0.05	0.06	0.07

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Table 11: Energy and Grid Electricity Use and Costs 2020-2030 (South Coast)

Scenario	Hydrological Scenario Wet			Hydrological Scenario Normal			Hydrological Scenario Dry		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Energy (TWh)									
Baseline	0.66	0.73	0.79	0.76	0.92	0.82	0.86	1.1	1.3
Population	0.67	0.73	0.79	0.77	0.92	0.81	0.87	1.1	1.3
GPCD	0.66	0.73	0.79	0.76	0.92	0.81	0.86	1.1	1.3
Landscape	0.66	0.73	0.79	0.76	0.92	0.82	0.86	1.1	1.3
Irrigation Efficiency	0.62	0.68	0.74	0.70	0.86	0.77	0.79	1.0	1.3
OPPE	0.63	0.70	0.75	0.73	0.87	0.78	0.82	1.1	1.3
Electrification	0.66	0.73	0.79	0.76	0.92	0.82	0.86	1.1	1.3
Grid Electricity (TWh)									
Baseline	0.59	0.64	0.69	0.67	0.81	0.73	0.76	1.0	1.2
Population	0.59	0.65	0.70	0.68	0.81	0.72	0.76	1.0	1.2
GPCD	0.59	0.64	0.69	0.67	0.81	0.72	0.76	1.0	1.2
Landscape	0.58	0.64	0.69	0.67	0.81	0.73	0.76	1.0	1.2
Irrigation Efficiency	0.54	0.60	0.65	0.62	0.76	0.68	0.70	0.92	1.1
OPPE	0.56	0.61	0.66	0.64	0.77	0.69	0.72	0.93	1.1
Electrification	0.60	0.66	0.71	0.68	0.83	0.74	0.77	1.0	1.2
Grid Electricity (billion $2018)									
Baseline	0.09	0.10	0.11	0.11	0.13	0.12	0.12	0.16	0.19
Low Growth	0.09	0.10	0.11	0.11	0.13	0.12	0.12	0.16	0.19
High Growth	0.10	0.10	0.11	0.11	0.13	0.12	0.12	0.16	0.19

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Table 12: Energy and Grid Electricity Use and Costs 2020-2030 (San Francisco)

Scenario	Hydrological Scenario Wet			Hydrological Scenario Normal			Hydrological Scenario Dry		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Energy (TWh)									
Baseline	0.14	0.15	0.15	0.15	0.16	0.17	0.16	0.17	0.20
Population	0.14	0.15	0.15	0.15	0.16	0.17	0.16	0.17	0.20
GPCD	0.14	0.15	0.15	0.15	0.16	0.17	0.16	0.17	0.20
Landscape	0.14	0.15	0.15	0.15	0.16	0.17	0.16	0.17	0.20
Irrigation Efficiency	0.14	0.15	0.16	0.15	0.16	0.18	0.16	0.18	0.20
OPPE	0.13	0.14	0.15	0.14	0.15	0.17	0.15	0.17	0.19
Electrification	0.14	0.15	0.15	0.15	0.16	0.17	0.16	0.17	0.20
Grid Electricity (TWh)									
Baseline	0.13	0.13	0.14	0.13	0.15	0.16	0.14	0.16	0.18
Population	0.13	0.13	0.14	0.13	0.15	0.16	0.14	0.16	0.18
GPCD	0.13	0.13	0.14	0.13	0.15	0.16	0.14	0.16	0.18
Landscape	0.13	0.13	0.14	0.13	0.15	0.16	0.14	0.16	0.18
Irrigation Efficiency	0.13	0.14	0.14	0.14	0.15	0.16	0.15	0.16	0.18
OPPE	0.12	0.13	0.14	0.13	0.14	0.15	0.14	0.15	0.17
Electrification	0.13	0.14	0.14	0.14	0.15	0.16	0.14	0.16	0.18
Grid Electricity (billion $2018)									
Baseline	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.03	0.03
Low Growth	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.03	0.03
High Growth	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.03	0.03

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Table 13: Energy and Grid Electricity Use and Costs 2020-2030 (San Joaquin River)

Scenario	Hydrological Scenario Wet			Hydrological Scenario Normal			Hydrological Scenario Dry		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Energy (TWh)									
Baseline	20.2	22.3	23.5	22.8	23.7	25.7	26.3	28.6	31.0
Population	20.2	22.3	23.5	22.7	23.7	25.6	26.3	28.6	30.9
GPCD	20.3	22.3	23.6	22.8	23.8	25.7	26.4	28.6	31.0
Landscape	20.2	22.3	23.5	22.8	23.7	25.6	26.3	28.6	31.0
Irrigation Efficiency	16.1	18.0	19.2	18.1	19.1	20.9	20.9	23.1	25.5
OPPE	19.9	21.9	23.1	22.3	23.3	25.1	25.8	28.1	30.5
Electrification	20.2	22.3	23.5	22.8	23.7	25.7	26.3	28.6	31.0
Grid Electricity (TWh)									
Baseline	18.4	20.3	21.5	20.7	21.7	23.4	23.8	25.8	27.8
Population	18.4	20.3	21.4	20.7	21.7	23.4	23.8	25.8	27.8
GPCD	18.4	20.3	21.5	20.8	21.7	23.4	23.9	25.8	27.9
Landscape	18.4	20.3	21.4	20.7	21.7	23.4	23.8	25.8	27.8
Irrigation Efficiency	14.6	16.4	17.5	16.4	17.4	19.0	18.8	20.8	22.9
OPPE	18.1	19.9	21.0	20.3	21.2	22.9	23.4	25.3	27.4
Electrification	18.7	20.6	21.8	21.0	22.0	23.7	24.2	26.2	28.3
Grid Electricity (billion $2018)									
Baseline	3.0	3.3	3.5	3.4	3.5	3.8	3.9	4.2	4.5
Low Growth	3.0	3.3	3.4	3.3	3.5	3.8	3.8	4.2	4.5
High Growth	3.0	3.3	3.5	3.4	3.5	3.8	3.9	4.2	4.5

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Table 14: Energy and Grid Electricity Use and Costs 2020-2030 (South Lahontan)

Scenario	Hydrological Scenario Wet			Hydrological Scenario Normal			Hydrological Scenario Dry		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Energy (TWh)									
Baseline	1.1	1.2	1.2	1.2	1.3	1.4	1.7	1.7	1.8
Population	1.1	1.2	1.2	1.2	1.3	1.4	1.7	1.7	1.8
GPCD	1.0	1.0	1.1	1.1	1.2	1.3	1.5	1.6	1.7
Landscape	1.1	1.2	1.2	1.2	1.3	1.4	1.7	1.7	1.8
Irrigation Efficiency	1.1	1.1	1.2	1.2	1.3	1.4	1.6	1.7	1.8
OPPE	1.1	1.1	1.2	1.2	1.3	1.3	1.6	1.7	1.8
Electrification	1.1	1.2	1.2	1.2	1.3	1.4	1.7	1.7	1.8
Grid Electricity (TWh)									
Baseline	1.0	1.1	1.1	1.1	1.2	1.3	1.5	1.6	1.7
Population	1.0	1.1	1.1	1.1	1.2	1.2	1.5	1.6	1.6
GPCD	0.89	0.94	1.0	1.0	1.1	1.1	1.4	1.4	1.5
Landscape	1.0	1.1	1.1	1.1	1.2	1.3	1.5	1.6	1.7
Irrigation Efficiency	1.0	1.0	1.1	1.1	1.2	1.2	1.5	1.5	1.6
OPPE	1.0	1.0	1.1	1.1	1.1	1.2	1.4	1.5	1.6
Electrification	1.0	1.1	1.1	1.1	1.2	1.3	1.5	1.6	1.7
Grid Electricity (billion $2018)									
Baseline	0.16	0.17	0.18	0.18	0.19	0.20	0.25	0.26	0.27
Low Growth	0.16	0.17	0.18	0.18	0.19	0.20	0.25	0.25	0.27
High Growth	0.16	0.17	0.18	0.18	0.20	0.21	0.25	0.26	0.27

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Table 15: Energy and Grid Electricity Use and Costs 2020-2030 (Sacramento River)

Scenario	Hydrological Scenario Wet			Hydrological Scenario Normal			Hydrological Scenario Dry		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Energy (TWh)									
Baseline	5.3	6.0	7.1	5.7	6.1	7.2	6.4	7.7	8.5
Population	5.3	6.0	7.1	5.7	6.1	7.2	6.4	7.7	8.5
GPCD	5.3	6.0	7.1	5.8	6.2	7.3	6.4	7.8	8.6
Landscape	5.3	6.0	7.1	5.7	6.1	7.2	6.4	7.7	8.5
Irrigation Efficiency	5.3	6.0	7.1	5.8	6.2	7.3	6.4	7.8	8.6
OPPE	5.0	5.7	6.7	5.4	5.8	6.8	6.0	7.3	8.1
Electrification	5.3	6.0	7.1	5.7	6.1	7.2	6.4	7.7	8.5
Grid Electricity (TWh)									
Baseline	4.8	5.4	6.4	5.2	5.6	6.5	5.9	7.1	7.7
Population	4.8	5.4	6.4	5.2	5.6	6.5	5.9	7.1	7.7
GPCD	4.8	5.5	6.4	5.2	5.6	6.6	5.9	7.1	7.8
Landscape	4.8	5.4	6.4	5.2	5.6	6.5	5.9	7.1	7.7
Irrigation Efficiency	4.8	5.5	6.4	5.3	5.6	6.6	5.9	7.1	7.8
OPPE	4.5	5.2	6.1	4.9	5.3	6.2	5.5	6.7	7.3
Electrification	4.9	5.5	6.5	5.3	5.7	6.7	5.9	7.2	7.9
Grid Electricity (billion $2018)									
Baseline	0.78	0.88	1.0	0.84	0.91	1.1	1.0	1.1	1.3
Low Growth	0.77	0.87	1.0	0.83	0.90	1.1	0.94	1.1	1.2
High Growth	0.79	0.89	1.0	0.85	0.92	1.1	1.0	1.2	1.3

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Table 16: Energy and Grid Electricity Use and Costs 2020-2030 (Tulare Lake)

Scenario	Hydrological Scenario Wet			Hydrological Scenario Normal			Hydrological Scenario Dry		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Energy (TWh)									
Baseline	39.3	42.3	45.2	50.9	53.8	56.9	71.5	75.5	81.0
Population	39.2	42.2	45.1	50.9	53.8	56.8	71.4	75.5	80.9
GPCD	39.3	42.3	45.2	51.0	53.9	56.9	71.5	75.6	81.0
Landscape	39.3	42.3	45.2	50.9	53.8	56.9	71.5	75.5	81.0
Irrigation Efficiency	32.0	34.9	37.6	43.1	45.7	48.4	61.9	66.0	71.4
OPPE	38.6	41.6	44.5	50.1	52.9	56.0	70.3	74.4	79.8
Electrification	39.3	42.3	45.2	50.9	53.8	56.9	71.5	75.5	81.0
Grid Electricity (TWh)									
Baseline	34.8	37.4	39.9	45.0	47.6	50.3	63.0	66.5	71.2
Population	34.7	37.3	39.8	45.0	47.5	50.2	62.9	66.4	71.1
GPCD	34.8	37.4	39.9	45.1	47.6	50.3	63.0	66.5	71.2
Landscape	34.8	37.4	39.9	45.0	47.6	50.3	63.0	66.5	71.2
Irrigation Efficiency	28.3	30.8	33.2	38.1	40.3	42.7	54.5	58.1	62.8
OPPE	34.2	36.7	39.2	44.3	46.8	49.4	62.0	65.5	70.1
Electrification	35.5	38.1	40.7	46.0	48.6	51.3	64.3	67.9	72.7
Grid Electricity (billion $2018)									
Baseline	5.6	6.0	6.5	7.3	7.7	8.1	10.2	10.8	11.5
Low Growth	5.6	6.0	6.4	7.2	7.6	8.1	10.1	10.7	11.4
High Growth	5.7	6.1	6.5	7.4	7.8	8.2	10.3	10.9	11.6

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Table 17: Grid Electricity Use 2020-2030: Major Electric Utilities (TWh)

Scenario	Hydrological Scenario Wet			Hydrological Scenario Normal			Hydrological Scenario Dry		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Pacific Gas & Electric									
Baseline	43.1	47.0	49.5	53.7	56.0	59.9	70.3	77.1	83.2
Population	43.1	46.9	49.5	53.7	56.0	59.9	70.2	77.1	83.2
GPCD	43.2	47.0	49.6	53.8	56.1	60.0	70.4	77.2	83.3
Landscape	43.1	46.9	49.5	53.7	56.0	59.9	70.3	77.1	83.2
Irrigation Efficiency	36.6	40.3	42.7	46.7	48.7	52.4	61.7	68.7	74.7
OPPE	42.3	46.1	48.6	52.7	54.9	58.8	69.0	75.7	81.8
Electrification	43.9	47.8	50.4	54.7	57.0	61.0	71.7	78.6	84.8
Southern California Edison									
Baseline	17.6	18.3	19.2	19.9	21.0	22.3	26.4	27.0	28.0
Population	17.6	18.2	19.1	19.8	20.9	22.3	26.4	27.0	28.0
GPCD	17.4	18.0	18.9	19.6	20.7	22.0	26.1	26.7	27.7
Landscape	17.6	18.3	19.2	19.9	21.0	22.3	26.4	27.0	28.0
Irrigation Efficiency	14.5	15.1	15.9	16.5	17.5	18.7	22.3	22.9	23.9
OPPE	17.2	17.9	18.8	19.5	20.5	21.9	25.9	26.5	27.5
Electrification	18.0	18.6	19.6	20.3	21.4	22.7	27.0	27.6	28.6
San Diego Gas & Electric									
Baseline	3.0	3.1	3.2	3.3	3.4	3.6	3.9	4.0	4.1
Population	3.0	3.1	3.2	3.3	3.4	3.6	3.9	4.0	4.1
GPCD	3.0	3.1	3.2	3.3	3.4	3.6	3.9	4.0	4.1
Landscape	3.0	3.1	3.2	3.3	3.4	3.6	3.9	4.0	4.1
Irrigation Efficiency	2.3	2.4	2.4	2.5	2.6	2.8	3.0	3.1	3.1
OPPE	3.0	3.0	3.1	3.2	3.4	3.5	3.9	4.0	4.0
Electrification	3.0	3.1	3.2	3.3	3.4	3.6	3.9	4.0	4.1

Source: GEI Consultants/Navigant Consulting, Inc., 2010

Table 18: Grid Electricity Use 2020-2030: Other Electric Utilities (TWh)

Scenario	Hydrological Scenario Wet			Hydrological Scenario Normal			Hydrological Scenario Dry		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
Northern California									
Baseline	0.9	1.0	1.0	1.3	1.5	1.6	2.9	4.2	4.9
Population	0.9	1.0	1.0	1.3	1.5	1.6	2.9	4.2	4.9
GPCD	0.9	1.0	1.0	1.3	1.5	1.6	2.9	4.2	4.9
Landscape	0.9	1.0	1.0	1.3	1.5	1.6	2.9	4.2	4.9
Irrigation Efficiency	0.8	0.9	0.9	1.2	1.4	1.5	2.8	4.0	4.8
OPPE	0.9	1.0	1.0	1.3	1.5	1.6	2.9	4.1	4.8
Electrification	1.0	1.0	1.0	1.4	1.5	1.7	3.0	4.2	5.0
Central California									
Baseline	1.6	1.6	1.7	1.7	1.8	1.8	2.1	2.2	2.3
Population	1.6	1.6	1.7	1.7	1.8	1.8	2.1	2.2	2.3
GPCD	1.6	1.6	1.7	1.7	1.8	1.8	2.1	2.2	2.3
Landscape	1.6	1.6	1.7	1.7	1.8	1.8	2.1	2.2	2.3
Irrigation Efficiency	1.2	1.2	1.3	1.3	1.3	1.4	1.6	1.7	1.8
OPPE	1.5	1.6	1.6	1.7	1.7	1.8	2.0	2.1	2.3
Electrification	1.6	1.6	1.7	1.7	1.8	1.9	2.1	2.2	2.4
Southern California									
Baseline	10.4	10.8	11.1	11.8	12.3	12.7	15.4	16.6	17.5
Population	10.4	10.7	11.0	11.8	12.2	12.7	15.4	16.5	17.5
GPCD	10.3	10.6	10.9	11.6	12.1	12.5	15.2	16.3	17.3
Landscape	10.4	10.7	11.0	11.8	12.3	12.7	15.4	16.6	17.5
Irrigation Efficiency	8.2	8.4	8.6	9.3	9.6	10.0	12.2	13.4	14.4
OPPE	10.3	10.6	10.9	11.6	12.0	12.5	15.1	16.3	17.3
Electrification	10.5	10.8	11.1	11.9	12.4	12.8	15.5	16.7	17.7

Source: GEI Consultants/Navigant Consulting, Inc., 2010

CHAPTER 5: Conclusions

This report projects both total energy and grid electricity use and costs for groundwater pumping in California. The estimates rely on a bottom-up model that combines water requirements and supply, groundwater depth, pumping efficiency, pump fuel, and grid electricity rates to calculate the amount of energy used to pump groundwater during the periods of 2005-2015 and 2020-2030, along with the corresponding values of grid electricity consumed and its cost. The estimates were developed at the level of DWR planning areas, aggregated into hydrological regions, and tailored for electric utilities (based on their service territories). Two groups of scenarios have been developed to inform projections of groundwater total energy and grid electricity use and costs. The first group is comprised of three sets of hydrological scenarios, each representing possible futures of wet, normal, and dry future years. The hydrological scenarios that only include years with normal hydrological conditions make up the baseline projections, and the wet and dry scenarios provide the lower (wet scenario) and upper (dry scenario) bounds for the projections. The other group of scenarios relates to changes in the main drivers of groundwater energy (e.g., agriculture and municipal indoor/outdoor water use, pumping efficiency) and tests which measures could reduce that energy requirement. It further includes one scenario that assumes full electrification of well pumps, with a significant penetration of solar and other renewables to power those pumps.

The largest use of groundwater grid electricity is in the agriculture-rich Central Valley. PG&E, SCE, SDG&E, and other electric utilities are most affected by groundwater pumping. This stems not only from the size of the territories they serve but also because of the presence of agriculture in their service area. Groundwater energy use is affected by changes in hydrological conditions mostly in the North Coast, Tulare Lake, North Lahontan, South Lahontan, and South Coast hydrological regions.

Several assumptions verified which measures could most effectively contribute to groundwater pumping energy reductions—from reducing municipal indoor and outdoor water consumption to increasing irrigation and well pumping efficiency. The measure that offers the greatest opportunity for reducing groundwater pumping energy is improving irrigation efficiency, especially in the Colorado River, San Joaquin River, Tulare Lake, and South Coast hydrological regions. Reducing the per capita indoor water use in the South Lahontan hydrological region, and improving pumping efficiency in the Sacramento River, South Lahontan, South Coast, and San Francisco hydrological regions would also contribute to reducing groundwater energy use.

The estimates in this report should be used cautiously for future policies and programs in the state. Groundwater data are scarce and sometimes hard to obtain; groundwater levels and other hydrogeological parameters, which significantly vary spatially, are not available for all regions in the state and are often of poor quality when they are available. Similar considerations apply to groundwater pumping efficiency. Future research should focus on how best to improve the accuracy of these results. Despite these limitations, the estimates developed in this project together provide the most detailed and comprehensive analysis of the state's groundwater energy requirements to date.

CHAPTER 6: Technology/Knowledge Transfer Activities

California relies significantly on groundwater to meet its water needs. The lack of a full, systematic recording of groundwater extractions poses challenges to understanding the drivers for groundwater pumping and estimating the energy needed to support that pumping. This is particularly critical during drought periods, when heavy pumping and the deepening of groundwater tables exacerbate the demand for energy to sustain groundwater extraction. A lack of understanding of programs that help reduce groundwater pumping energy additionally prevents energy planners from accurately predicting increases in pumping efficiency and its associated energy reductions.

Lawrence Berkeley National Laboratory (LBNL) was funded by the California Energy Commission (CEC) to conduct research to estimate near-term past and future electricity use and cost for groundwater pumping in California. Results from the research project are relevant to stakeholders engaged in California's energy and water sectors. This document highlights LBNL's plan to share the knowledge gained in this project to state agencies, academic researchers, electric utilities, and other affected stakeholders.

6.1: Project Background

The goal of this project was to address a key knowledge gap in California's energy-water nexus puzzle: the grid-electricity required to pump groundwater in the state. The project offers a comprehensive look at how energy and groundwater interact in California, and provides the basis for estimating energy demand for groundwater pumping under alternative climate and policy scenarios. The study is organized into four parts. The first part explains how groundwater pumping data and other information was collected and organized. The second part uses that data to estimate relevant empirical relationships between factors that determine the amount of energy required to pump groundwater. The third part surveys groundwater pumpers on their current groundwater pumping practices and assesses barriers and incentives for improving energy efficiency and water conservation. Finally, the fourth part of the study uses the relationships developed in the second part to estimate near-term groundwater pumping energy use and its cost across the state under alternative climatic conditions. It further relies on findings from the third part of the study to simulate how estimated energy and cost could be reduced with enhanced pump efficiency and water conservation.

Results from the project enable stakeholders (e.g., state agencies, electric utilities, water planners, and large pumped-water users) were used to develop robust projections of energy use and costs as well as strategies to reduce groundwater use and its pumping energy and energy costs. Overall, the expanded knowledge provided by the study supports more cohesive energy-water planning efforts in California, particularly in light of more prevalent prolonged drought conditions.

6.2: Project Dissemination

Findings from this project have been strategically shared with stakeholders since its earliest stages. In May 2017, the project was introduced to participants of the Groundwater Workgroup of the *Association of California Water Agencies* (ACWA) during its 2017 Spring Conference in Monterey, California. Project information has also been disseminated to a broad spectrum of stakeholders by members of the project's Technical Advisory Committee (TAC):

- California Department of Food and Agriculture
- California Department of Water Resources
- California Public Utilities Commission
- California State Water Resources Control Board
- City of Fresno
- City of Santa Rosa
- Irrigation Training and Research Center (Cal Poly)
- Pacific Gas and Electric Company
- Powwow Energy
- Regional Water Authority
- San Luis & Delta-Mendota Water Authority
- U.C. Davis
- U.C. Kern Cooperative Extension
- U.C. Santa Barbara
- United States Department of Energy
- Westat

A survey was also conducted to reach the municipal water agencies, irrigation districts, and growers that pump groundwater. Survey recruitment fliers were distributed at: the 3rd Open Farm, UC Kearney Agricultural Research and Extension Center, Parlier, in October 2018; ACWA 2018 Fall Conference, San Diego, in November 2018; Pistachio Research Board's Pistachio Day, Visalia, in January 2019; and the California Irrigation Institute's 57th Annual Conference, Sacramento, in February 2019. Fliers were also distributed by a TAC member to municipal water agencies and irrigation districts that belong to the San Luis & Delta-Mendota Water Authority. ACWA and the California Water Efficiency Partnership (CalWEP) emailed its members about the surveys, as did the Groundwater Resources Association, the Natural Resource Conservation District, and the East Merced Resource Conservation District. The *Farm Journal* emailed approximately 6,000 growers. The University of California Agriculture and Natural Resources (UCANR) Cooperative Extension emailed around 200 farm specialists and advisors and UC faculty to request that the survey be featured with growers they work with. Additionally, the surveys were featured in newsletters from the California Association of Resources Conservation districts and the California Climate and Agriculture Network; in the *Maven's Notebook*; in the California Farm Bureau Association's *Ag Alert*; and in the UCANR's peer-reviewed journal, *California Agriculture*. The survey of farmers and ranchers was posted on the *Facebook* page of the Almond Board of California, tweeted by Fresno State's Center for Irrigation Technology, and featured in an article in *Ag Net West* and broadcast (radio) in its

Farm City Newsday podcast. Finally, the survey of growers was also advertised several times in the California Farm Bureau Association's *Ag Alert* newspaper.

6.3: Knowledge Transfer

The research team will continue to share project results with state agencies, academic researchers, electric utilities, and other relevant stakeholders through both the project's TAC members and third parties. This information will also be shared with the municipal water agencies and irrigation districts that contributed groundwater data, and with those who indicated in their survey questionnaires they wanted to receive the survey report.

The team will also summarize results from this project in two LBNL technical reports. One report will include the data collection, organization, analysis, and estimates of groundwater electricity use and its cost. The other report will summarize survey efforts and results. The team also plans to submit a paper to a journal. The paper will summarize the data and the methodological and modeling approaches used to estimate near-term total energy and grid-electricity use and costs for groundwater pumping in California.

Chapter 7: Benefits to Ratepayers

7.1: Introduction

This research project quantified the energy used for pumping groundwater and identified efficiency measures for lowering energy use. A major goal of the project was to identify feasible energy efficient technologies (e.g., better pumps) and practices (e.g., better irrigation, conservation) that those users can adopt to reduce pump energy use. Better, more disaggregated estimates of groundwater energy use along with estimates of savings potential will help the State and utility manage drought conditions, reduce customer utility bills, improve forecasting of future electric loads, and thus support electric sector resource planning.

An important outcome of this work are factors that allow user groups to overcome barriers to adopting conservation strategies. At this point, it is not known the degree to which this work will encourage users to adopt energy and water efficient technologies and practices. The team, nevertheless, estimates this project may reach total annual benefits of $100 million. Below are benefits the team estimated to user groups and ratepayers, assuming that they fully adopt the energy and water efficiency technologies and practices identified. IOU ratepayers may benefit from this work through effects, including:

- Lower energy costs from increased adoption of pump use efficiency measures.
- Environmental benefits, including air quality and aquifer quality benefits.
- Increased electrical system reliability from improved demand forecasts.
- Lower electricity rates from reducing both electricity demand for groundwater pumping and uncertainties related to that demand.

7.2: Quantified Benefits

Conservation measures available to groundwater users in California include:

1. Improvements to pump efficiency.
2. Improvements to farm-irrigation efficiency.
3. Groundwater management.
4. Urban water-use efficiency.

The research team also estimated groundwater pumping and energy use from those measures, evaluated reductions in air emissions related to those savings, and estimated the monetary values of those benefits.

Potential Pump Efficiency Energy Savings

A 2006 American Council for an Energy-Efficient Economy (ACEEE) study indicates that average annual Central Valley groundwater electricity use is 2,250 GWh, and that average pump efficiency in the Central Valley is 70 percent (Wilkinson et al., 2006). Assuming the same electricity use today, a 10-percent increase in pump efficiency just in the Central Valley could save ratepayers about 250 GWh annually.

Potential Irrigation Efficiency Energy and Water Savings

The same 2006 ACEEE study suggests that improvements to agricultural irrigation efficiency could decrease annual agricultural pumping requirements between 0.2 and 0.8 million acre-feet. Given that it requires an average of 200 kWh to pump an acre-foot of groundwater in much of the state (Wilkinson et al., 2006). Assuming a similar decrease in pumping requirements today, irrigation-efficiency measures could potentially conserve between 40 and 160 GWh of electricity annually.

Potential Energy and Water Savings From Groundwater Management

Groundwater management and recharge programs could potentially reduce groundwater use about one million acre-feet annually—roughly 10 percent of annual average groundwater pumping in the Central Valley. Using groundwater management to raise groundwater pump depths by 10 percent could potentially conserve about 225 GWh of electricity use annually.

Potential Energy and Water Savings From Urban-Water Efficiency Measures

Urban water-use efficiency measures could potentially save about 2 million acre-feet of water annually. Urban areas, like agricultural areas, use groundwater to supply about 30 percent of their 9 million acre-feet of annual water demand (Wilkinson et al., 2006). Therefore, urban water-use conservation could conservatively eliminate the need for 0.6 million acre-feet of groundwater pumping. Although the pumping depths to groundwater are not known precisely, 200 kWh per acre-foot provides a reasonable approximation of average pump electricity needs in urban California. This value suggests that urban water use efficiency programs could potentially save 120 GWh of electricity per year.

These potential savings suggest that pump efficiency, irrigation efficiency, groundwater management, and urban water efficiency programs together offer total potential savings of 600-750 GWh of electricity and 1.8-2.4 million acre-feet of water for groundwater consumers and utility ratepayers. The savings amount to around 3.6 percent of the electricity used in agriculture and water pumping and 2.4 percent of the water used in the state. They can help prevent long-term groundwater depletion and avoid the increased electricity required to pump water from depleted aquifers. The savings will also avoid emissions of around 330,000 tons of CO_2 and 450,000 pounds mass (lbm) of NO_x, assuming emission factors of 0.49 ton of avoided CO_2 per MWh and 0.67 lbm of avoided NO_x per MWh.

The potential benefits from full adoption of groundwater efficiency measures can be expressed monetarily. At an estimated retail price of electricity of $0.15/kWh, the potential energy savings would be worth $90-115 million annually. In addition, at an estimated carbon value of $12/ton, the potential carbon emissions benefits of the project are worth $4 million annually. Under those assumptions, the team estimates the total annual benefits of the project could reach $100 million.

7.3: Additional Benefits

This study further improves system reliability by helping utilities more accurately predict energy consumption from groundwater pumping. For example, current forecast methods appear to understate electricity demand for groundwater pumping, which is assumed to represent 5 percent of California's total electricity use; recent reports suggest the actual amount is closer to 7 percent. As for peak-load reduction, it is difficult to evaluate the impacts of potential peak-load mitigation measures since almost all urban groundwater pumping occurs at night during off-peak hours.

Impacted Market Segments in California

The most critically affected market segments are those that rely on groundwater as significant sources of their water supplies. Irrigated agriculture accounts for over 70 percent of total groundwater consumption in California, so most attention should focus on this user group. Public supply is the second most important segment of groundwater users in the state (estimated to be 23 percent of total groundwater consumption). Surveys conducted during this research project focused on growers, public groundwater users, and factors that explain groundwater uses and conservation behaviors.

Qualitative or Intangible Benefits to California Utility Ratepayers

There are several benefits that could follow from this project in addition to the energy and water savings benefits described, assuming that water districts and other users adopt both conservation methods and high-efficiency strategies. These include:

- Benefits to water and air quality flowing from reduced groundwater pumping.
- System reliability benefits from improved methods that forecast electricity demand.
- Benefits to the quality and sustainability of aquifers that could result by decreasing groundwater pumping and groundwater overdraft.
- Benefits to crop yield of adopting water-efficient irrigation technologies.

These benefits could be substantial by the end of this study's projected horizon.

The team also identified topics that will assist water districts when designing mandated groundwater management plans required by the *Sustainable Groundwater Management Act* (SGMA), including:

- Available policies and technologies for preventing groundwater overdraft and decreasing electricity consumption.
- Barriers confronting households, farmers and districts that prevent adoption of these policies and technologies.
- Factors to increase the likelihood that households, farmers, and districts will adopt these policies and technologies.

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