ECONOMICS OF POSSIBLE ENERGY SECTOR ROLES IN A FOOD ENERGY WATER STRESSED REGION

A Dissertation

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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August 2019

Major Subject: Agricultural Economics

ABSTRACT

South Central Texas is a region where water is scarce, the region exhibits growing water, energy and food demands associated with an expanding population. Climate change also stresses water supplies. This dissertation examines electricity sector possibilities for alleviating water scarcity in a Food-Energy-Water (FEW) Nexus context. In particular, possibilities for retrofitting existing cooling systems of power plants to reduce water withdrawal and consumption are considered.

To evaluate water related actions by regional power plants, an examination is done of the water savings and associated cost arising from potential changes in cooling systems. The estimated costs per acre foot of water saved for converting existing recirculating cooling systems over to dry cooling systems were found to be $9,315 per acre-foot of water saved. This cost is generally higher than most currently identified regional water development possibilities, only being competitive with the most expensive under current consideration. If cooling conversion is to be done it will more likely done to accommodate reductions in available water and increase in associated reliability.

Analysis is also done on the demands placed on the electricity sector as the region evolves into the future. We find population growth, climate change and growing water demands substantially change electricity demand, cause construction of new power plant supply capacity, and increase cooling water use. In particular, power supply capacity is increased in order to meet the growing electricity demand from the population and new water supply projects. Also, in select cases, power plants retrofit recirculating cooling systems to dry cooling systems to conserve water.

DEDICATION

To my dear family

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my committee chair, Dr. Bruce A. McCarl for his excellence guidance and persistent help. It has been an honor to be his student, his guidance helped me in all the time of research and writing of this dissertation. I could not have imagined having a better advisor and mentor for my Ph.D study. Besides my advisor, I also would like to thank my committee members, Dr. Ximing Wu, Dr. Reid Stevens, and Dr. Rabi H. Mohtar, for their insightful comments and support throughout the course of this research.

I would also like to express my thanks to Drs. Robert Hogan and Gerald Cornforth from Texas A&M Agrilife Extension for their comments on the development of crop and livestock data, Nattie Gonzalez from Texas Water Development Board providing water use data, Drs. Raghavan Srinivasan and Essayas K.Ayana from Department of Ecosystem Science and Management, Dr. Bassel Daher from Department of Biological & Agricultural Engineering, Dr. Rudy Rosen from Texas A&M University in San Antonio, Dr. Efstratios N. Pistikopoulos, Dr. Styliani Avraamidou, Yaling Nie and Cory Allen from Texas A&M Energy Institute for their supports in the constructing of FEW Nexus model. Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience.

Finally, thanks to my mother and father for their encouragement and support, and to my husband for his patience and love.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a dissertation committee consisting of Professors Bruce A. McCarl, Ximing Wu, Reid Stevens of the Department of Agricultural Economics and Professor Rabi H. Mohtar of the Department of Biological & Agricultural Engineering.

All work for the dissertation was completed by the student with collaboration. Specifically, the economic aspects of FEW Nexus in Chapter 2 are coauthored with Dr. Bruce A. McCarl. He also suggested the consideration of conserving water via electrical cooling option in Chapter 3. Modeling in Chapter 4 is a collaboration work with Chengcheng Fei from Department of Agricultural Economics.

Funding Sources

Graduate study was supported by Graduate Teaching Assistantships from the Department of Agricultural Economics, and research grants by the National Science Foundation under Grant Addressing Decision Support for Water Stressed FEW Nexus Decisions Number 1739977; Texas A&M University Water Energy Food Nexus Initiative under Grant 2017 FEW Nexus Summit: Integrated Science, Engineering, and Policy: a Multi Stakeholder Dialogue Number 1707019. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the organizations mentioned above.

NOMENCLATURE

FEW Nexus	Food-Energy-Water Nexus
EAA	Edwards Aquifer Authority
CPMP	Critical Period Management Plan
USGS	United States Geological Survey
TCEQ	Texas Commission on Environmental Quality
PDSI	Palmer Drought Severity Index
RCP	Representative Concentration Pathway
MW	Megawatt
MWh	Megawatt Hour
EIA	Energy Information Administration
TWDB	Texas Water Development Board
NGCC	Natural Gas Combined Cycle
EPA	Environmental Protection Agency
DCR	Dry Cooling Retrofit
SWAT	Soil & Water Assessment Tool
GCM	Global Circulation Model
IPCC	Intergovernmental Panel on Climate Change

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1. INTRODUCTION

The intersection of decision making regarding food, energy, and water is known as the food-energy-water (FEW) Nexus. The FEW Nexus elements are strongly interlinked. Food production is intimately linked to water through rainfall, irrigation and water needs in processing. Water use often requires energy for pumping. Energy production can involve substantial amounts of water for power plant cooling, fracking, and hydroelectric generation. The purpose of considering FEW Nexus interrelationships is to identify and capitalize on synergies and in turn pursue FEW coordinated actions rather than uncoordinated actions. The basic assumption is that decisions based on the Nexus-wide considerations will produce additional benefits relative to a focus on individual elements.

The FEW Nexus topic has not been extensively studied from an economic viewpoint with few studies advancing Nexus wide analytical tools, but the definitional discussion has been extensive. Bazilian et al. (2011) describe some directions for addressing the Nexus and presents the attributes of a modelling framework that can support effective policy design. Miralles-Wilhelm (2016) proposes a research agenda that stresses the need to build integrated mathematical modeling of the FEW Nexus. Ringler, Bhaduri and Lawford (2013) present a framework to evaluate the linkages among water, land, energy and food, they also identify measures to reduce the costs of tradeoffs and enhance synergies among the sectors. Daher and Mohtar (2015) develop a FEW Nexus modelling tool which offers a common platform for scientists and policy-makers to evaluate scenarios and identify sustainable national resource allocation strategies. This dissertation presents a Nexus model that integrates across agricultural, hydrologic and energy concerns covering the full scope.

This study focuses on FEW Nexus issues under water scarcity covering resource management and allocation decisions. South Central Texas is a region where water is scarce while water, energy and food demands are growing due to an expanding population. Furthermore, expensive regional water supply schemes are being proposed to meet the growing demands. Water scarcity hinders: 1) meeting the water demands of a rapidly growing municipal sector; 2) maintaining endangered species protection; 3) continuing an active irrigated crop production sector; 4) supplying current and possibly growing cooling water demands for power plants; 5) accommodating fracking water demands; and 6) coping with the projected water deficit. Collectively, the complexity of the system has stimulated more comprehensive planning and may be benefited by yet wider Nexus based approaches.

Changes in climate are also likely to impact all elements of the Nexus with regional projections for hotter and drier conditions. Crop yields for irrigated and dryland crops as well as crop irrigation water requirements are directly influenced by precipitation and temperature. Water supply is sensitive as higher temperatures lead to greater evaporation losses that diminish water supply as does reductions in precipitation. Changing temperature and precipitation can expand nonagricultural water demand. Rising air and surface water temperatures both increase cooling water needs for power plants. Hotter conditions raise municipal energy demands. Climate change thus makes interactions and dependencies between FEW sectors even more complex.

This study addresses FEW Nexus issues at the intersection of agriculture, water, electricity, population growth, and climate change. This will be done with particular focus on the electricity sector. The objectives of this study are:

- Understanding how and at what cost manipulations in power sector cooling can reduce power water demands. This involves both using dry cooling in new power plants and retrofitting existing power generating plants. We will focus on changes in cooling systems within South Central Texas thermal electric power plants.
- Examining the effects of water project and population growth on electricity demands and means of meeting those demands.
- Understanding the effects of climate change on the situation.

To do this work I will contribute to the development of an integrated FEW Nexus model in particular developing an electrical power component. In turn this model will be used to examine the effects of population growth, climate change and Nexus conditions on the electricity sector.

Specifically, in this thesis chapters we will address the following topics:

- Chapter 2 presents a literature review on FEW Nexus analysis and economic considerations involved with FEW decision making and modeling.
- Chapter 3 presents the results of an analysis on the cost of conserved water via manipulating electrical power plant cooling. This will be done under current climate and future climate change. Additionally, a comparison will be done between the cost of water supplied by changing electrical cooling and a set of Texas Water Development Board (TWDB) proposed regional water supply and conservation projects.
- Chapter 4 presents a modeling-based analysis on the role of power plant cooling and added construction actions within regional Nexus decision making. Boiler retrofits from coal to natural gas will also be examined. In doing this current and future conditions will be studied including the effects of population growth and climate change. Overall, we will examine electricity demand, wholesale electricity price, electric power supply capacity, and welfare.

- Chapter 5 presents concluding comments plus information on limitations and possible further research.

2. BACKGROUND AND LITERATURE REVIEW*

In this chapter, we will review FEW issues regarding the region and the economics of FEW Nexus decisions. In terms of the region we will cover its characteristics, including the access to aquifers, contained river basins, regional water supply and conservation possibilities, climate conditions, agricultural activity, and energy production/use. In terms of economics we will discuss and review major economic issues involved when considering potential FEW Nexus actions, including: 1) incorporating market reactions and prices; 2) behavioral reactions of individuals to Nexus actions; 3) non-market valuation; 4) transfer of results between studies; 5) value of water in alternative uses; 6) economic influences on observed Nexus strategies; 7) designing incentives; 8) induced innovation; 9) adding consideration of limits; and, 10) welfare consequences of actions.

2.1. The Study Region

Within this work the South Central Texas case study region is that part of Texas bounded to the west by the Nueces basin and to the east by the Guadalupe and San Antonio basins (Figure 2.1). The figure overviews the geographic and hydrologic scope of the region showing it contains: 1) four river basins: Nueces, San Antonio, Guadalupe, and San Antonio-Nueces river basins; 2) four aquifers: the Edwards, the Carrizo Wilcox, the Gulf Coast, and the Edwards Trinity aquifers; 3) part or all of 42 Texas counties.

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*Part of this chapter is reprinted with permission from Introduction to the Food-Energy-Water Nexus, by Bruce A. McCarl, Yingqian Yang, edited by Peter Sanudry and Benjamin L. Ruddell, Springer forthcoming.

Figure 2.1 South Central Texas Rivers, Aquifers

The region is also part of Regions L and N in the Texas water planning activity. Therein regional population projections indicate region L which includes the San Antonio metropolitan area, is expected to increase by 73 percent from 2020 to 2070, and region N population which includes the Corpus Christi metropolitan area, is expected to increase by 21 percent from 2020 to 2070. Water demand in region L is projected to increase by 34 percent, from 1.07 million acre-feet in 2020 to 1.43 million acre-feet in 2070. Simultaneously, the region L planning group projects existing water supplies will be 1.03 million acre-feet in 2020, and 1.02 million acre-feet in 2070. This shows a region L water deficit of 410,000 acre-feet of water by 2070. The total water use for region N is projected to increase by 16 percent, from 279,738 acre-feet in 2020 to 324,037 acre-feet in 2070. The existing water supply are 278,782 acre-feet in 2020, and 308,425 acre-feet in 2070. Thus, again region N faces a deficit. This regional water scarcity has motivated us to develop a FEW Nexus model to address the long-term and short-term regional water needs and its impact on FEW components.

Below we introduce the characteristics of FEW components in this study.

2.2. Aquifers

As shown in the regional map, the aquifers analyzed in this study are: 1) the Edwards Aquifer, 2) the Carrizo Wilcox Aquifer, 3) the Gulf Coast Aquifer, and 4) the Edwards Trinity Aquifer.

2.2.1. The Edwards Aquifer

The Edwards Aquifer in South Central Texas is one of the most permeable and most productive aquifers in the world (Maclay 1995). The San Antonio segment of the Edwards Aquifer covers an area approximately 160 miles long and 5 to 40 miles wide, and is located through six counties (Kinney, Uvalde, Medina, Bexar, Comal, and Hays). The aquifer is the main water source for the city of San Antonio and surrounding communities. It also provides water for the region's agricultural and industrial sectors as well as spring flows for endangered species habitat in the Comal and San Macros Springs, and in turn springs from the Edwards Aquifer provide base flow to the Guadalupe River.

Recharge to the Edwards Aquifer occurs primarily from streams as they cross the recharge zone in the western part of the aquifer (Lindgren et al. 2005; Maclay 1995). Additional recharge is from rainfall infiltration. Annual total recharge ranges from 43,700 acre-feet in 1956 at the height of the record drought to 2,486,000 acre-feet in 1992. The variation is shown in Figure 2.2. Annual total pumping and spring discharge estimates range from 388,800 acre-feet in 1955 to 1,130,000 acre-feet in 1992.

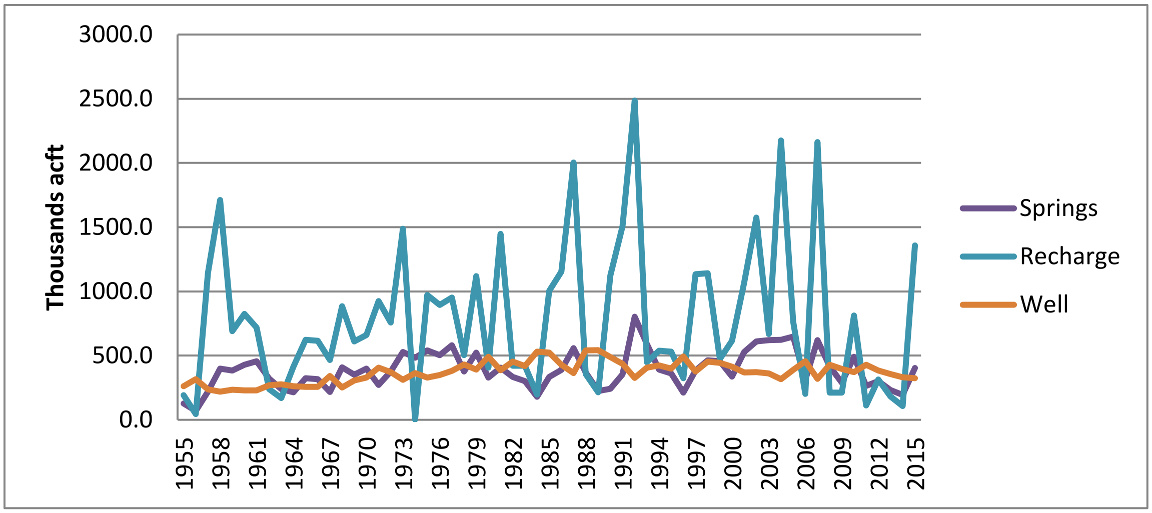


Figure 2.2 Annual Edwards Aquifer recharge and discharge

The Edwards Aquifer Authority (EAA) Act was adopted by the Texas Legislature in 1993 in response to the legal threat of a federal takeover of aquifer management under the Endangered Species Act. The Act created the EAA and directed the EAA to manage the aquifer withdrawals. To maintain the stream flows, the EAA adopted a Critical Period Management Plan (CPMP) to control pumping during droughts. Based on the critical period aquifer level and spring flow triggers the EAA decides the percentage of withdrawal reduction. The EAA divides the aquifer into two pools and has index wells for gauging elevation in both: the Uvalde Pool and the San Antonio Pool. Each pool has different triggers, and the triggers are based on the 10-day average of the rate of spring flow at Comal or San Macros springs, and the elevations at the two index wells. When the index well levels or spring flow rate falls below a certain threshold, EAA will implement varying degrees of pumping reductions as shown in Table 2.1.

Table 2.1 Critical period triggers, stages, and withdrawal reductions

San Antonio Pool

Trigger	Critical Period Stage 1	Critical Period Stage 2	Critical Period Stage 3	Critical Period Stage 4	Critical Period Stage 5
(Based on 10-day average)					
Index Well J-17 Level (MSL)	<660	<650	<640	<630	<625
San Macros Springs Flow (CFS)	<96	<80	N/A	N/A	N/A
Comal Springs (CFS)	<225	<200	<150	<100	<45/40
Withdrawal Reduction	20%	30%	35%	40%	44%
Uvalde Pool					
Trigger	Critical Period Stage 1	Critical Period Stage 2	Critical Period Stage 3	Critical Period Stage 4	Critical Period Stage 4
(Based on 10-day average)					
Index Well J-17 Level (MSL)	N/A	<850	<845	<842	<840
San Macros Springs Flow (CFS)	N/A	N/A	N/A	N/A	N/A
Comal Springs (CFS)	N/A	N/A	N/A	N/A	N/A
Withdrawal Reduction	N/A	5%	20%	35%	44%

The Uvalde Pool is located west of the Frio River, and mainly receives recharge from the Nueces River Basin. The Uvalde Pool provides irrigation water, spring flows at Leona Springs, flow into the San Antonio Pool, and storage in the Uvalde Pool. The San Antonio Pool is located east of the Frio River and west of New Braunfels. It is the primary source of municipal water for the San Antonio metropolitan area but also provides irrigation water and spring flow at Comal and San Macros Springs. The San Antonio Pool receives recharge from the Uvalde Pool as well as from the eastern part of the Nueces river and from the San Antonio, and western part of the Guadalupe River Basins.

Hydrological evidence suggests that a constriction known as “Knippa Gap” separates the Uvalde Pool from the San Antonio Pool. The “Knippa Gap” acts as a barrier limiting water passage. In addition, a large amount of recharge from the Frio and Dry Frio Rivers at the

"Knippa Gap" doubles the amount of groundwater flow (Green et al. 2006). The effect of the structural constriction and focused recharge at the "Knippa Gap" caused water level in the Uvalde Pool to be higher and less variable than that in the San Antonio Pool.

Because of the aquifer's highly permeable nature, water levels and spring flows respond quickly to rainfall, drought, and pumping. Although well water levels periodically and seasonally can rapidly decline throughout the aquifer, they also rebound quickly with adequate rainfall. As is shown in Figure 2.3, two monitoring wells indicate historical annual water level fluctuations, where J17 Well monitors the San Antonio Pool, and J27 Well monitors the Uvalde Pool. Droughts in 1956, 1966, 1970, 1984, 1988, 1996, 2006, 2009, 2011, and 2014 are apparent in J17 Well levels, but in many years the well recovers quickly after a drought year.

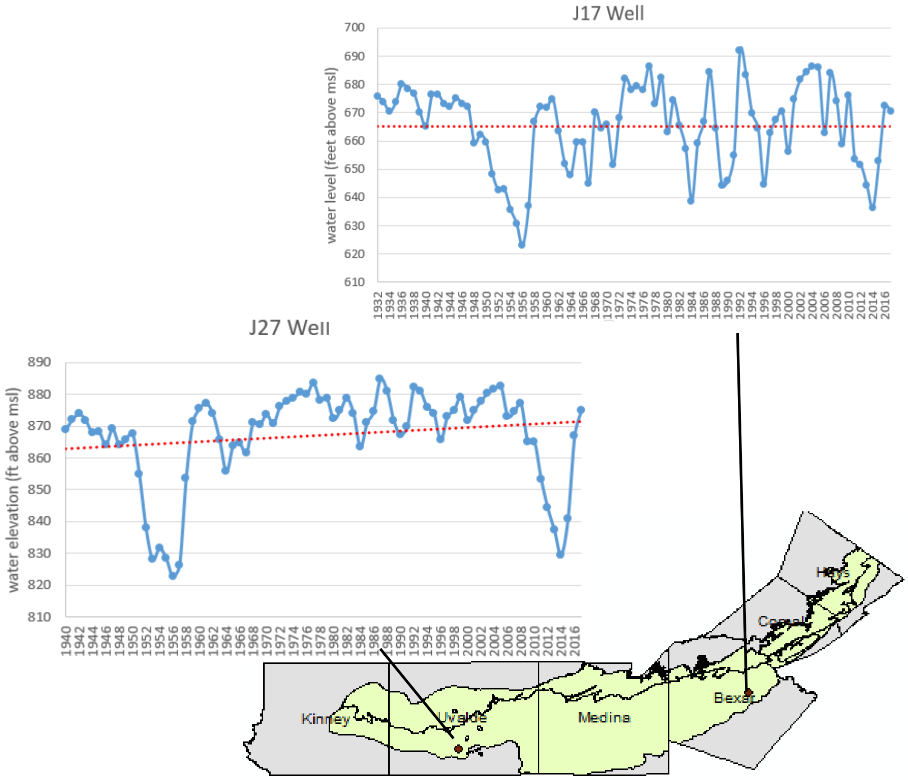


Figure 2.3 Water elevation in J17 Well and J27 Well in feet above mean sea level

2.2.2. The Carrizo Wilcox Aquifer

The Carrizo Wilcox Aquifer consists of the Carrizo Sand and the Wilcox Group. Substantial water movement occurs between the Carrizo Sand and the Wilcox Group, thus, the two units are treated as one aquifer system (River and NAWQA 2000). The Carrizo Wilcox Aquifer can be broken down into three regions: northern, central, and southern. Our focus here is the southern Carrizo Wilcox, which is bounded on the northeast by the surface water basin divide between the Guadalupe and Colorado Rivers and to the southwest by the Rio Grande (Deeds et al. 2003).

The main source of recharge in the southern Carrizo Wilcox Aquifer is precipitation, main channel stream recharge and flood flow recharge (Deeds et al. 2003). The volume of recharge has been estimated by a Groundwater Availability Model and proprietary surface water models developed by HDR Engineering (LBG-Guyton Associates and HDR Engineering 1998). In the study, the potential annual recharge ranges from a low of 1,614 acre-feet estimated for Uvalde County to a high of 21,582 acre-feet per year estimated for Atascosa County.

Historically, irrigation and fracking activities have been the largest withdrawal from the southern Carrizo Wilcox Aquifer, particularly in Atascosa, Zavala, and Frio Counties, as these counties are located in areas of agricultural Winter Garden and Eagle Ford Shale Geological Area for oil and gas production. Municipal use of water from the aquifer is expected to increase. As a result of pumping induced water level declines, discharge towards streams tends to change from being gaining in early times to losing over time from east to west across the study region. Discharge also occurs in areas where the water table intersects the surface at springs (Deeds et al. 2003).

Variations in water levels result from changes in storage, recharge and discharge from the aquifer. Three wells are shown in Figure 2.4, representing the drawdown of ground water level, all of them are drilled to Layer 5 of the Carrizo Wilcox Aquifer, located in areas of Winter Garden where large amounts of ground water are withdrawn for irrigation. Well 7708511 is in Frio County, and is drilled to a depth of 1450 feet below the land surface. Well 7738103 is in La Salle County, and is 2084 feet deep. Well 7702509, in Zavala County, is drilled to 734 feet. The fluctuations in water level (feet below land surface in Figure 2.4) in these three wells reflect seasonal variations in irrigation withdrawals. Well records indicate low water levels during the drought in 2014. All of these three wells show aquifer drawdown with falling water levels as the depth below the land surface is progressively higher over time.

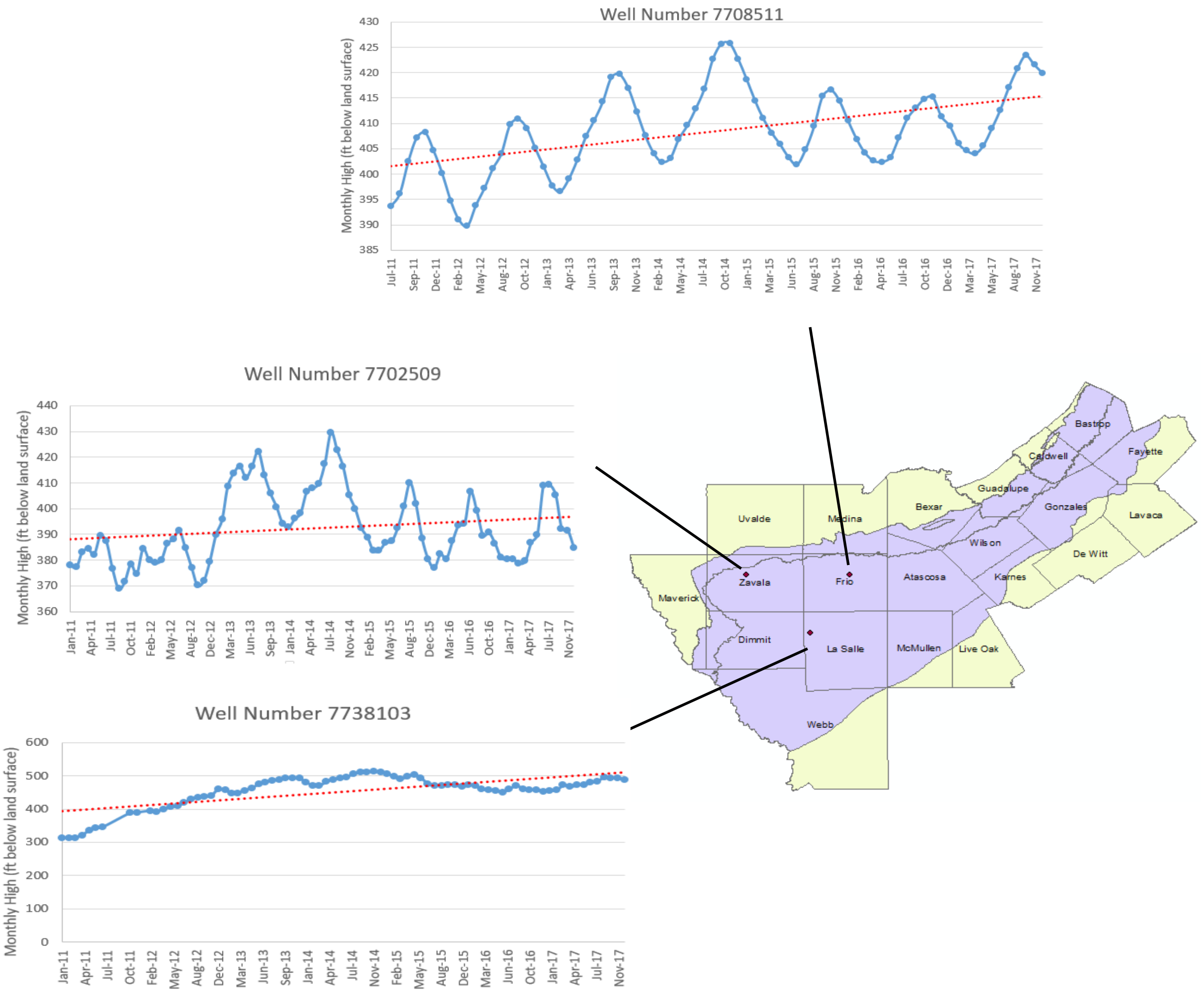


Figure 2.4 Wells showing water-level variations (feet below land surface) in Carrizo Wilcox Aquifer

Groundwater Management Areas were created in order to conserve, protect, and prevent over drafting of groundwater and there is such for the Carrizo Wilcox Aquifer. In Groundwater Management Area 13, covering most of the counties in the southern segment of the Carrizo Wilcox Aquifer, the stated desired future condition is an average drawdown of 48 feet from year 2012 to the year 2070 (Hutchison 2017). However, localized drawdown in some areas will likely exceed this amount, for example, as displayed in the Figure 2.4, the water of the well in Zavala County was around 370 feet below land surface in late 2012, and it was about 430 feet below land surface in the middle of 2014, the drawdown was about 60 feet, it had exceeded the desired future condition proposed by the Groundwater Management Area. The direct impact of aquifer drawdown is increased pumping cost for sectoral water use.

2.2.3. The Gulf Coast Aquifer

The central portion of the Gulf Coast Aquifer is in the study region. That segment of the aquifer has been divided into four components: 1) the Chicot Aquifer; 2) the Evangeline Aquifer; 3) the Burkeville Confining System; and 4) the Jasper Aquifer.

Recharge mainly occurs from rainfall that falls on the aquifer outcrop, and also from streams that cross the Aquifer. Several investigators have estimated recharge rates in the outcrop areas for the Gulf Coast Aquifer do not exceed 6 inch/year, and the rates are lower in the west than in the east (Ryder 1988; Dutton and Richter 1990; Groschen 1986; Kasmarek and Robinson 2004; Ryder and Ardis 1998). There are some variations in recharge due to local variations in rainfall distribution, evapotranspiration rates, groundwater-surface water interaction, and hydraulic conductivity.

Most of the pumping in the Gulf Coast Aquifer occurs from the Chicot and the Evangeline Aquifers (Mace et al. 2006). Groundwater from the aquifer is used for irrigation, industrial, and municipal purpose, however, some of this resource is not directly usable due to its moderate to high salinity. In the future, utilization of groundwater from the aquifer system will include use of brackish water that will be treated to provide a product acceptable for municipal, industrial, and other uses.

Three wells in the central portion of Gulf Coast Aquifer reveal different trends in water level change as shown in Figure 2.5. Two wells (well number 8017502 and 8415702) in the

Evangeline Aquifer, exhibit moderate (2 to 25 feet) increase in water levels in Victoria and Duval Counties due to a switch to surface water supplies and an accompanying reduction in groundwater pumping, since the high rates of land subsidence has forced a reduction in pumping along the coast. The third well (well number 7934009) in Bee County, drilled to the Chicot Aquifer, indicates water level has dropped slightly since 2011.

Most of counties overlying the central segment of aquifer are located in Groundwater Management Area 15 or 16. The Desired Future Condition for the counties in the Groundwater Management Area 15 is that the average aquifer drawdown should not exceed 13 feet between the years 2000 and 2070 (Young 2016). The Desired Future Condition for Groundwater Management Area 16 is that the average aquifer drawdown should not exceed 63 feet between 2010 and 2070 (O’Rourke 2017). Goswami (2017) estimated available groundwater for the Gulf Coast Aquifer System from approximately 748,000 acre-feet per year in 2020 to approximately 930,000 acre-feet per year in 2070. This estimate meet the Desired Future Condition adopted by the two Groundwater Management Areas.

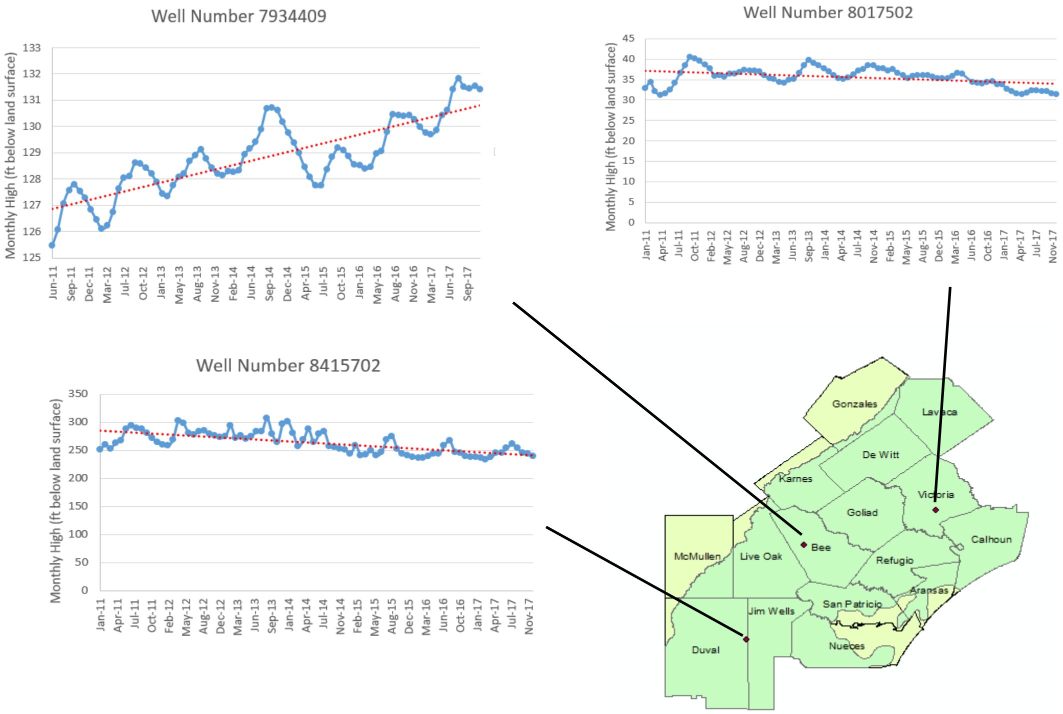


Figure 2.5 Wells showing water level variations in Gulf Coast Aquifer

2.2.4. The Edwards Trinity Aquifer

The Edwards Trinity Aquifer is a major aquifer extending across much of the southwestern part of the state. It is hydraulically connected to the Trinity and the Edwards Aquifers. The water-bearing units are composed of the Edwards Group and the Trinity Group. The lower unit is the partially confined Trinity Group and is extended to the Hill Country. The upper unit is the unconfined Edwards Group.

In the Edwards group, up to 4 percent of the annual precipitation enters the aquifer as recharge over the aquifer outcrops or from losing streams. In the Hill Country area, recharge over to the Trinity Group is about 4 to 6 percent of annual precipitation. The Trinity Group main discharge is to its pumping wells mostly but, groundwater also flows out of the Trinity Group as springs and base flow to gaining streams as well as flow to the Edwards Aquifer (Anaya and

Jones 2009). Water levels have remained relatively stable because recharge has generally kept pace with the relatively low amounts of pumping over the extent of the aquifer. Irrigation, the largest water use, is primarily located in the northern and western portions of the aquifer, and is estimated to be more than around 40,000 acre-feet/yr. All other groundwater withdrawals, public supply, industry, rural domestic, and livestock amount are estimated at less than 2,000 acre-feet/yr (Kuniansky and Ardis 2004).

2.3. Surface River Basins

South Central Texas region includes the Nueces, San Antonio, Guadalupe, and San Antonio-Nueces Coastal river basins. The Nueces River rises in Edwards County and flows to Nueces Bay near Corpus Christi. According to United States Geological Survey (USGS), approximately 60% of the recharge to the Edward Aquifer comes from the upper Nueces basin. The San Antonio River and Guadalupe River both recharge and gain flow from Edwards Aquifer. The two river systems join prior to discharge into San Antonio Bay.

Existing surface water supplies of the region include those derived from storage reservoirs and run-of-river water rights. Use of surface water in the state requires water right permits. Water right owners can divert a limited amount of water by obtaining the permits issued by the Texas Commission on Environmental Quality (TCEQ). Run-of-river water rights for the Nueces River are about 120,000 acre-feet/yr and are primarily for irrigation purposes. Consumptive run-of-river rights in the Guadalupe and San Antonio River Basin total over 446,000 acre-feet/yr and are primarily for irrigation, municipal, and industrial purposes (SCTRWPG 2015).

2.4. Climate Conditions

Water scarcity is becoming a problem in South Central Texas due to rapid population growth and shrinking water supply. Climate change is likely to affect regional water supply and demand, so it may make the water scarcity problem even more severe.

Cook, Ault and Smerdon (2015) report projections of the summer season Palmer Drought Severity Index (PDSI) and integrate soil moisture from the surface to 30 cm and 2 m depths projections. The projections are for 2050-2099 in Southwest and Central plains in the US and are based on results from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) using the RCP 8.5 emissions scenario. The consequent PDSI projections are for a more negative index and indicate drier than average conditions. The soil moisture index projections also indicate drying. The drought condition in the future reduces availability of water supplies, while concurrently increase demand for water.

South Central Texas Region is classified as humid subtropical. Its location between a semi-arid area to the west and a much wetter and more humid area to the east often results in large variations in monthly and annual precipitation amounts. Rainfall in Texas is enhanced in the fall and winter during positive (El Niño) phases of the El Niño Southern Oscillation and suppressed during negative (La Niña) phases. Thus, the onset of drought over Texas is often associated with La Niña events. According to National Oceanic and Atmospheric Administration (NOAA), La Niña patterns in 2016 and 2017 contributed to a warmer than normal winter, and 2011 was the warmest La Niña on record in Texas. Water availability in our study region is likely to be influenced by La Niña, as La Niña years are associated with low recharge (Chen et al. 2005a).

2.5. Regional Water Management Plan

The regional water scarcity has motivated the regional water planning group to actively engage in the development of water plans to address the long-term and short-term regional water needs.

The region L and region N water planning groups, have identified a variety of water management projects that would overall provide more water than is required to meet future needs. These water management projects include: 1) reusing water; 2) developing new fresh ground water supplies; 3) developing brackish ground water supplies; 4) employing aquifer storage and recovery approaches; 5) constructing new reservoirs; 6) desalinating seawater; and 7) developing new surface water supplies.

2.6. Electricity

Major types of thermoelectric power plants in the region are coal fired and natural gas, renewable plants such as wind and solar power plants have also grown rapidly. There are 55 existing plants in total, about half of them are thermal plants and half of them are renewable plants. These plants have the capacity to produce more than 15,438 MW of power, actual generation totals about 45,628,000 MWh, annually.

According to Energy Information Administration (EIA), regional electricity demand in 2016 was about 50,000,000 MWh, and per capital residential use of electricity is high in the summer and winter. Moreover, TWDB water projects include energy use in pumping and moving water long distances, which create potentially a large amount of electricity demands. For example, seawater desalination project uses pipeline to move water to San Antonio region, plus pumping energy use and water treatment, the total electricity for this project amounts to 148,260

MWh per year. We compared annul plant generation and regional electricity demand from EIA database, and found that this region currently has electricity gap.

In a typical thermoelectric power plant, heat is removed from the cycle with a condenser. In order to remove the heat, cooling water is used. The majority of water use for electricity generation is the cooling of thermoelectric power plants. Water consumption is an important indicator to determine power plant impacts and vulnerabilities associated with water resources. Surface water is widely used in cooling of electric power generation in the region, and consumptive water use for cooling purposes accounts for 20 % of total surface water use in the region.

2.7. Agriculture

According to the 2012 Census of Agriculture, 17 percent of the South Central Texas croplands were irrigated while the remaining 83 percent used dryland techniques. The TWDB irrigation water demand projections show annual irrigation use will decline by 18 percent from 2020 to 2070 based upon expected increase in irrigation efficiency and reductions in profitability of irrigated agriculture. The Winter Garden region is an agricultural area in the South Central Texas in Dimmit, Zavala, Frio, and LaSalle counties. This region is an area for irrigated agriculture. The major crops grown include corn, grain sorghum, winter wheat, soybeans, and cotton. Corn and grain sorghum have historically been the leading crops in the region. The leading corn producing counties in the region are Medina, Uvalde, and Victoria. The leading grain sorghum producing counties in the region are Refugio, Nueces, Victoria, Jim Wells, and San Patricio. The leading winter wheat producing counties in the region are Uvalde, Frio, Medina, and Guadalupe. Because of favorable climatic and soil conditions, the coastal counties of Calhoun and Victoria are able to produce rice. Cotton production is widespread throughout the region. Leading counties for cotton production were Medina, Refugio, Nueces, and Uvalde.

Major types of livestock produced in our study region include: goats, sheep, and cattle. Goats are adapted to the dry, rugged and brushy Texas Hill Country, thus the western part of our study region is home to the majority of the regional goats. Most of the sheep are raised in the Edwards Plateau, where nearly one third of our study region's counties are located. There are two types of sheep: hair sheep and wool sheep, the main difference between them is that the later produce wool. Calf stocker and cow calf operations are predominant types of cattle production in our study region. Calf stocker operations utilize available forages to grow calves until ready for entrance into the feedlot. Cow calf pairs operation is a method of raising cattle in which a permanent herd of cows is kept to produce calves for sale. According to the Census of Agriculture in 2012, livestock production was valued at 1.9 times the value of crops in the study region. Although livestock production is an important component of the regional economy, the industry consumes a relatively small amount of water.

2.8. Economic Aspects of FEW Nexus

FEW Nexus studies cover a significant portion of the broader category of natural resource economics. Bazilian et al. (2011) conclude that treating the three areas of the FEW Nexus holistically "would lead to a more optimal allocation of resources, improved economic efficiency, lower environmental impacts and better economic development conditions, in short, overall optimization of welfare". In doing this, we list economic considerations for FEW Nexus modeling drawing upon issues identified (McCarl and Yang Forthcoming).

2.8.1. Incorporation of Demand and Supply Relations

In the Nexus context, demand and supply curves indicate the way consumer price reacts to changes in output supply or the way input price reacts to alterations in input usage. A FEW project can both add extra supply to the market and alter input usage leading to market price changes which alters the revenue and cost outcomes of the project.

For example, increased production of corn-based ethanol in the United States has contributed to price increase for corn. In fact, corn prices in 2011 were triple those in 2005 (note other forces contributed as discussed in Abbott et al. 2011). In 2017, corn prices are more than 50 percent greater than 2005 levels. These significant price changes have diverted land to corn production. In turn, the increased corn-based ethanol production results in altered water use in many regions and more rapid depletion of ground water stocks.

Demand relationships are also key when Nexus actions cause product prices to increase. For example, The Washington Public Power Supply System (WPPSS), in the early 1970s, observed that regional electricity use was growing at 7% per year and responded by initiating construction on five nuclear generating facilities. Subsequently, as part of the need to finance the plants, they began to raise electricity rates which led to a demand response in the form of lowered electricity consumption, and the needed revenue for the financing did not materialize. Eventually this result in the abandonment of four of the plants and the largest bond default in history. This shows it is essential to incorporate product demand relations in the Nexus project evaluations.

2.8.2. The Rebound Effect

Economists have noted in many cases that subsidization of conservation actions, like use of energy efficient appliances or water conserving technology, can stimulate market responses which decrease the effectiveness of the action and have named this the "Rebound Effect" (Greening, Greene and Difiglio 2000). However, Nexus projects are often analyzed under a strong assumption that the current economic and technical characteristics of those using the conservation item will be unchanged.

In terms of a specific example, several western US states subsidized water conserving irrigation technologies, and assumed that only the equipment would change. However, Pfeiffer and Lin (2014) analyzed such a case in Kansas and found this lowered water costs to farmers and stimulated production of higher water using crops and expansions onto previously unirrigated lands resulting in increased overall water use. Thus, one needs to consider possible water and energy uses increases in usage when Nexus projects lower water or energy usage costs.

2.8.3. Non Market Valuation

Nexus projects often alter abundance or characteristics of items that don't trade in the marketplace like altered water quality, changes in air pollution, changes in greenhouse gas emissions (GHG), alterations in recreational access, and many other phenomena. In economics, it is the study of nonmarket valuation. For example, replacing a coal fired generating plant with solar energy may not be cost efficient in terms of fuel and equipment, but would also reduce air pollution and GHG emissions which would make the project more desirable. Valuing changes in air pollution and GHG emissions involves determining how much concerned society would need to be paid to live with diminished air quality and atmospheric GHG content or, how much they would be willing to pay to increase air quality and GHG content. A lot of techniques have been introduced to value such elements, such as the estimated “cost of carbon”, various revealed approaches, stated preference approaches. (Heal et al. 2005; Freeman III, Herriges and Kling 2014; Johnson and Hope 2012).

2.8.4. Can I Transfer Results from Other Assessments into This One

Frequently, results from other studies are used in a Nexus evaluation rather than developing primary estimates. A big issue in such a setting raises what economists call "benefits transfer" which refers to transfer of benefit estimates from some other location into the differing project location(Rosenberger and Loomis 2017). For example, Young (2010) contains a number of water value estimates from various region. However, such transfers need to be done with caution. Brouwer (2000) argues that most transfers appear to result in substantial transfer errors.

In covering benefits transfer the Ecosystem Valuation website developed by King, Mazzotta and Markowitz (2000) states "The more similar the sites and the recreational experiences, the fewer biases will result" and then presents a discussion and cites the benefits of such an action as :

- Reductions in the cost of carrying out an appraisal;
- Speed of attaining the information;
- Ability to use the transferred estimate in constructing a rough estimate on the value a project to see if more effort on it is justified; and
- Ability to use in making a gross estimate of the total item value (i.e. cost of water or reduced erosion).

It also cites the limitations as:

- Appropriate studies may not be published and are hard to access;
- Reporting in the studies found may not give one enough information to allow transferring the information with appropriate adjustments;
- Quality of the other studies may be difficult to assess;
- Extrapolation beyond what is covered in the initial study is questionable;
- The accuracy of the transferred item is limited by that of the item itself; and estimates may be out of date.

2.8.5. Value of Water in Alternative Uses

It is important to develop information on the value of water in alternative uses, such as irrigation, ecological support, downstream urban, pollution dilution, hydro-electric use, cooling, and fracking. These differential values exist because of high costs of moving water and historical water allocation procedures (like prior appropriation water rights). Comparison of water's value in various uses and locations allows one to look at the implications of Nexus based reallocations.

A number of market and nonmarket valuation approaches have been developed to estimate value of water in alternative uses (Young 2010). Consumers' surplus which represents the total dollar amount consumers would be willing to pay minus what they actually must pay for could be used as market valuation approach, and it is useful in valuing water when a demand curve for water can be estimated. Colby (1989) argues that in most regions water is not bought and sold in a competitive market setting making determination of the demand curve difficult and suggests a number of methods. Basically, these are:

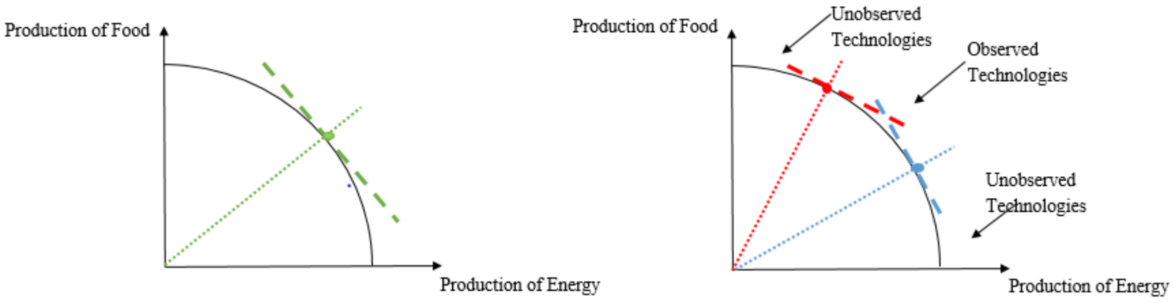
1) A comparable sales approach which involves comparison of specific water one is trying to value with the prices and characteristics of similar water that has been recently sold or leased;
2) A land value differentials approach which assumes the value of water is capitalized into land values and involves comparison of the values of agricultural land with and without water access;
3) A replacement approach which involves estimation of cost or replacing the water from the lowest cost alternative water supply source; and
4) In the rare case, an econometric estimate of water demand can be formed where trading data can be attained along with sufficient information on other characteristics of the trade (i.e. Is the water conveyed from a senior or junior right? or Is the transfer permanent or a lease? and What are the lease terms?).

2.8.6. Economic Influences on Observed Nexus Strategies

A tempting way of identifying possible Nexus strategies is observation of prior actions that address the Nexus either in the target region or in similar regions. In such a case, there is an inherent bias in what can be observed that arises due to economic prices. In particular, the range of prices that have been observed for both output and inputs restrict what Nexus opportunities may have been chosen and thus can be observed. Let us look at theoretical examples of this.

In setting up this example, we use the classical production possibilities curve as in Figure 2.6. The bold black line in panels A and B gives a continuous set of energy-food production possibilities using different technologies. Each point on the curve represents choice of a technology which results in a certain level of food production (y-axis) and energy production (x-axis). Thus, lower energy production correlates to higher food production or visa-versa. In panel

A, the green dotted line gives the ratio of the food price to the energy price. According to economic theory, the production technology chosen will be the one at the point where there is a tangency between the line giving the price ratio and the production possibilities curve. This means production in our case will occur where the green dotted line is tangent to the bold line - at the green dot.



Panel A: Optimal Choice Given a Price Panel B: Domain of Strategies Given a Price Range

Figure 2.6 Production possibilities curve and items chosen

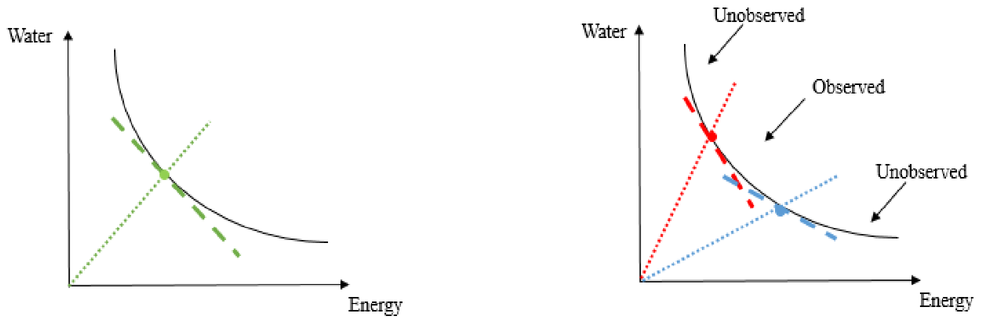
Now given this basic setup, consider panel B where we have a red line representing the highest observed ratio of food price to energy price and the blue line representing the lowest ratio. Then in this case, the only Nexus technologies we have observed fall between the two dotted points and those outside that arc will not have been seen.

A second example can be cast in terms of inputs using the classical isoquant that explains the relative use of two inputs given their prices as in Figure 2.7. Therein assume the bold line in panel A gives a continuous set of possible quantities of energy and water used across the set of possible technologies. Also assume the dotted line gives the ratio of the energy price to the water price.

According to economic theory, given the input price the production technology chosen is the one at the point where there is a tangency between the line giving relative prices of energy and water as occurs at the green point in panel A. Now given this basic setup, consider panel B where we have a red line representing the highest ratio of energy price to water price we have ever seen and a blue line representing the lowest ratio. Then in this case, the only Nexus possibilities we have observed fall between the two colored dots and again there are a lot of unobserved possibilities that never got chosen because the prices did not favor them.

However, Nexus actions or external forces can alter production possibilities, isoquants and relative prices. Under such shifts, previously unattractive Nexus related production or resource usage strategies can become desirable. Thus, not all possible strategies will be observed and new never before seen strategies may arise.

As a consequence, identifying Nexus related strategies through surveys, interviews or other means will not generally describe the full set of possible strategies that may arise in the future.



Panel A: Optimal Choice Given a Price   Panel B: Domain of Strategies Given a Price Range

Figure 2.7 Production isoquant and strategies chosen

2.8.7. Induced Innovation

New technologies are likely to evolve as input or product prices change where the technologies make less use of more expensive items and more of those with falling prices. This has been called induced innovation(Hicks 1963; Ruttan and Hayami 1984). The theory indicates that when the price of a factor of production increases (falls) sharply relative to the price of other factors, society will innovate by developing technologies that reduce (increase) usage of that factor.

In a Nexus setting, an example is that when water prices dramatically increase due to scarcity, society will invent ways of substituting other factors for water, like going to the more capital-intensive drip irrigation. Similarly, if a fee is charged for GHG emissions, this will induce industry and others to develop strategies that produce goods with less emissions.

2.8.8. Adding Consideration of Limits

In looking at Nexus strategies one needs to examine and quantify the limits to strategy adoption. Chambwera et al. (2014) characterize such limits as:

1) Financial capital availability;
2) Human education and abilities;
3) Resources available;
4) Consistency with cultural practices;
5) Availability of technology; and,
6) Knowledge of new practices.

Limits may be alleviated through educational programs, extension programs, loan programs, grants and other actions. They may also simply render some strategies useless.

2.8.9. The Role of Incentives

It is rarely the case that a FEW Nexus action will make everyone better off (what economists commonly call an action that is Pareto optimal). Generally, at least one participant in the Nexus or a group thereof will be made worse off by the given action. In such a case, economists generally utilize the compensation principle (Hicks 1939; Kaldor 1939) finding that the action is desirable if those gaining from the implementation have gains large enough to compensate those who lose (Just, Hueth and Schmitz 2008). In this case, there is no guarantee that the compensation will actually occur. However, if the individuals that would implement the Nexus action are disadvantaged, then some form of direct compensation is likely needed to get the Nexus action implemented.

Compensation in the form of incentives can stimulate implementation by target entities by overcoming their losses and others may pay if they benefit more than the cost of the incentives. Steps can also be taken to make current practices undesirable, steering decision makers to implement the Nexus action. Many different forms of incentives or steering disincentives are possible, including:

1) The introduction of markets for Nexus items, like a water market, where gainers can buy the water from those who would lose if not using the water where the price compensates for any losses;
2) The introduction of subsidies for the equipment used in the desirable action, reducing the costs of the equipment directly or reducing the cost of money borrowed to buy the equipment;

3) The introduction of taxes on equipment crucial to continuation of current practices making them unattractive;
4) The use of technology standards which mandate an upgrade in technology to the desirable actions such as café standards on vehicle miles per gallon; and,
5) The development of differentiated markets favoring products from Nexus implementing parties, for example, opportunities to purchase electricity only from renewable sources.

In implementing such incentives, one naturally needs to be careful about inducing the rebound effect as discussed above, and also will need to be flexible potentially altering prices in order to get the amount of resource transferred that is desirable.

2.8.10. Welfare

An economic concept that is relevant to Nexus decision-making involves welfare. Economic welfare is a monetary measure of the gains (or losses) achieved by consumers from having cheaper, more abundant (more expensive, scarcer) Nexus products. It also measures the gains to producers in the form of profits from having more Nexus resources available or losses under the converse. Welfare estimates the willingness to pay to avoid some sort of negative force like pollution, or the willingness to accept compensation in the face of a Nexus management practice being adopted that worsens their well-being. The producer component is called producers' surplus. The consumer component is called consumers' surplus.

The welfare effects of adopting a Nexus practice involve both producers and consumers welfare. This is an important distinction because many Nexus type studies only estimate the effect on producers without considering any consumer effects. The consumer benefits arise from cheaper product prices or greater product availability at a given price.

In general, treatment of consumers' effects means incorporating demand curves and assumptions other than fixed-prices for commodities. In particular, as more is produced then, assuming that the market share is significant, this will cause prices to go down giving consumers more for their money or the converse occurs with prices going up.

Overall, it is useful to do a welfare analysis in conjunction with the evaluation of a Nexus project on recognized groups of producers and consumers (i.e. farmers, electricity producers, low income consumers, urban dwellers, rural parties, overseas parties etc.) as opposed to an aggregate analysis. Such a welfare analysis is commonly called an income distribution analysis. There is also one result that is often confusing for some that merits explanation. Often actions that increase supply decrease producers' surplus but benefit consumers, while action that reduce supply are beneficial to producers but not consumers. This occurs since agriculture and energy both typically face an inelastic demand curve and less supply raises prices substantially benefiting producers but causing consumers to reduce the amount of goods they buy, while more supply lowers prices and producer incomes but causes the consumers dollar to go farther.

2.9. Conclusion

In this chapter, we reviewed the background information of South Central Texas, also we identify economic issues in FEW Nexus modeling. We feel if those challenges are overcome it will improve the ease, accessibility, usefulness, and accuracy of FEW analyses. Such well-designed FEW models will advance the ability to analyze water, energy, and food Nexus issues in several ways, including the following: (a) increasing stakeholder and analyst understanding of Nexus-wide linkages across and within FEW sectors; (b) improving understanding of management action implications; and (c) facilitating appropriate linkage of unifying models with component food, water, and energy modeling systems.

3. CLIMATE CHANGE AND THE COMPARATIVE COST OF CONSERVED WATER VIA ELECTRIC COOLING OPTIONS: A FEW NEXUS CASE STUDY IN SOUTH CENTRAL TEXAS

3.1. Introduction

Cooling water usages for thermoelectric power generation represent a major withdrawal of water in the United States and in Texas. In 2010 thermoelectric power users withdrew 45% of all Texas water withdrawals and 46.4% of all Texas freshwater withdrawals (Maupin et al. 2014). Furthermore, surface water is the source for nearly all such withdrawals. The high surface water reliance puts cooling water supplies and thus power production at risk in times of drought. Strategies such as retrofitting existing cooling systems to reduce water withdrawal and consumption are possible water conservation options to mitigate water scarcity, release water for other uses and reduce drought risk.

Human needs for water and energy grow with population. Over the coming decades, climate change is expected to be another stressor on water and energy generation. Thermal power plants are vulnerable to climate change globally (Schaeffer et al. 2012; Roy et al. 2012; Vliet et al. 2012). In particular, climate change can lower river flows affecting water availability and can raise air and surface water temperatures both increasing cooling need and lessening the cooling effect of water, both of which increase water demand. This would also raise the temperature of any water released back to the river raising additional environmental concerns (Macknick et al. 2011). In fact, the temperatures of summer 2011, put most of Texas in “exceptional drought” and forced at least one power plant to downscale operations (Scanlon, Duncan and Reedy 2013). Torell and Stevens (2018) find that generators with water-intensive cooling technologies respond to exceptional drought conditions by raising their average bid prices.

This chapter reports on an economic investigation of cooling options as a potential way of releasing water for other uses and is done as part of an exercise to analyze the water-energy Nexus in South Central Texas. This chapter also involves the impact of climate change on cooling water use for power plants, and examines the cost of altering cooling systems under both current condition and projected climate change conditions.

3.2. Background on Cooling Systems in Use

Cooling water is used in thermal power generation to cool steam allowing more efficient electricity generation. Multiple cooling designs are used including once-through systems, recirculating systems (also referred to as cooling towers), and air-cooled condensers.

Once-through cooling systems operate by withdrawing relatively large volumes of water from a river or lake, then using that water to absorb heat from the steam, subsequently discharging it but at a higher temperature. In this case, consumptive use is a small fraction of the water withdrawn. Once-through cooling systems are considered undesirable as they have negative environmental impacts on aquatic organisms due to water intake and the release of heated water. Section 316(b) of The Clean Water Act requires the location, design, construction, and capacity of cooling water intake structures to employ the best technology available for minimizing adverse environmental impacts(EPA 2004) and this has resulted in Environmental Protection Agency (EPA) prohibiting new once- through cooling systems since 2001. Today few power plants use once-through cooling. Retrofitting existing once-through plants with recirculating technology reduces the water diversions and can help alleviate competition for limited fresh water supplies plus have environmental advantages.

A **recirculating cooling system**, instead of discharging hot water, uses a cooling tower or a cooling pond to reduce the heat content allowing water reuse. Recirculating cooling systems only withdraw water to replace evaporative losses, diverting relatively smaller volumes of water compared to once-through cooling systems.

Dry cooling systems use air, instead of water, to cool steam. The large capital costs of dry cooling system make them less common (Strzepek et al. 2012). Also, dry cooling is less energy efficient increasing plant fuel usage, in turn increasing variable operating costs. However, dry cooling systems do not use cooling water, greatly reducing water withdrawals (dry cooling plants also require water for maintenance and cleaning), plus decreasing consumptive water use by more than 90 percent. They also alleviate water scarcity and drought issues.

3.3. Literature Review on Cooling Water Use and the Water Energy Nexus

This is not the first economic study of cooling alternatives in the context of the water-energy Nexus for power plants. Some studies have focused on cooling water system technologies in thermal power plants. Stillwell and Webber (2013) evaluated the feasibility of retrofitting alternative cooling technologies in Texas power plants. They found that while cooling tower and dry cooling systems require additional capital and increase operating expenditures, that part or all of these expenses can be offset with revenue from leasing water rights that are not needed due to lessened water use under the new cooling technologies. They also point out that this also makes the power plant less vulnerable to drought.

Loew, Jaramillo and Zhai (2016) conducted a cooling system retrofit study based in Texas. They estimated the marginal costs of water withdrawal reductions for recirculating and dry cooling retrofits, their results demonstrated that replacing once-through cooling at coal-fired power plants with wet recirculating towers has the lowest cost per unit of reduced water withdrawal.

Tidwell et al. (2014) analyzed water usage associated with US based cooling conversions from recirculating cooling systems employing wastewater and brackish water to dry cooling alternatives. They estimate that dry cooling is on average \$12.31/MWh more expensive than employing a wastewater based recirculating system and \$6.59/MWh than a brackish groundwater based one. They also estimate that a brackish groundwater based recirculating cooling system using is \$1.35/MWh more expensive than a wastewater based one.

There are also studies that have considered fuel switching as a means to reduce water use (Grubert, Beach and Webber 2012; Pacsi et al. 2014; Peer et al. 2016; Sanders et al. 2014). They estimate that replacing Texas coal fired plants with natural gas combined cycle plants (NGCCs) would reduce statewide freshwater consumption by an estimated 53 billion gallons per year, largely due to the higher efficiency of NGCCs.

Studies also examined the effects of water use fees. Sanders et al. (2014) studied the implications of adding fees from \$10 to \$1000 USD per acre-foot for water withdrawals in Texas finding that water saved through fee increases was more expensive than that under TWDB proposed long-term water supply projects.

Studies have also examined water use for new thermal power plants in the context of changing regulatory environments and future power plant needs(Zhai and Rubin 2016; Talati, Zhai and Morgan 2014). They found new NGCCs consume roughly 60-70% less water than coal plants over a range of possible future emission standards from 1100 to 300 lb CO_2/MWh gross.

Water use may also change for new plants due to the EPA New Source Performance Standard (NSPS) rule. However, recent administrative actions place implementation of this rule in doubt. Nevertheless, that rule would if implemented, effectively ban new coal-fired generation construction since the most technologically advanced plants cannot meet the emission per megawatt-hour standards. Thus, if this rule is implemented, new plants will likely be natural gas or renewable power plants. Most new natural gas generation plants will likely be NGCC, which have higher heating value efficiency (Hsu et al. 2012). Renewable power plants have grown rapidly, particularly in Texas. CPS Energy, San Antonio's municipally-owned utility, announced plans to generate half of all electricity from renewable sources by 2040.

3.4. Objectives and Contribution

In this chapter we focus on water savings and associated cost arising from potential changes in cooling systems within South Central Texas power plants. This region has significant thermal electric plant capacity, growing demand for both water and energy, and is facing water scarcity. According to TWDB region L and region N water planning reports(CBRWP 2015; SCTRWPG 2015), consumptive water use in South Central Texas for steam electric plants in 2020 is projected to account for 20 percent of total regional surface water use. Simultaneously climate change is forecast to both increase temperatures and decrease surface water flows. One possible power plant response is to lessen dependence on cooling water.

This study considers the cost associated with altering cooling systems in individual power plants estimating the capital, operation and maintenance (O&M) costs, as well as the changes in water use. This will be done under both current conditions and under projected climate change. The results will be reported in terms of dollars per acre-foot of water consumption saved. Subsequently, we will compare water cost via cooling system retrofits with the costs estimated when implementing TWDB identified regional water conservation projects.

3.5. Power Plant Conversions and Characteristics

Possible strategies to conserve on water include: 1) converting once-through cooling systems to recirculating cooling or dry cooling systems; 2) converting recirculating cooling systems to dry cooling systems; and, 3) converting coal fired boiler to natural gas boiler. When retrofitting once-through cooling systems to recirculating cooling systems, consumptive water use in fact increases, so we omit our analysis on retrofitting once-through cooling systems to advanced cooling systems. Also, when we consider retrofitting boilers, we found there are 4 coal fired power plants in the region using recirculating ponds as cooling systems, consumptive water use for this type of cooling system is affected by factors such as evaporation, size of the pond, and seasonality. Thus, because of data inaccuracy on consumptive water use that using recirculating ponds, this study will only consider recirculating towers to dry cooling alternatives as data were not available for water consumption with fuel source changes. In terms of recirculating tower plants, ten plants were selected for cost estimation.

Data on individual power plant characteristics are within EIA databases containing power plant data from EIA's Forms 860 and 923. EIA Form 860 collects annual data on existing US power plant equipment (including generators, boiler, cooling systems and air emission control systems). EIA Form 923 collects information on power plant operations (including electric power generation, fuel consumption, cooling water quantity, and operational data for emission control, etc.). The Form 860 data were used to classify power plants by fuel type (coal and natural gas), and prime mover technology (steam, combustion and combined cycle). Form 923 data was used to gain information on monthly generation and in cases water use by individual plants.

3.6. Water Usage Assessment

The EIA Form 923 data includes reported monthly water withdrawal and consumption; however, the data are incomplete with some natural gas power plants omitted. Additionally, several papers have argued that data quality is a concern (King, Duncan and Webber 2008; Dieter et al. 2018; Averyt et al. 2013). The data for several power plants report water withdrawal and consumption exhibit levels that are far different from engineering estimates. Mittal(2010) argues this occurred because “respondents may use different methods to measure or estimate data, and instructions may be limited or unclear, plus respondents may make mistakes or have nontechnical staff fill out surveys”. As we could not find public information on consumptive water use in thermal power plants, we developed an alternative regression-based approach to estimate it.

3.6.1. Estimation Methodology

Climate factors such as temperature and precipitation can directly impact consumptive cooling water use. We first examining how power plant generation was influenced by ambient temperature and precipitation then use that information to estimate consumptive water use as a function of temperature, precipitation, generation, capacity. Then, we calculate the direct and indirect climate effects on consumptive water use.

The data used in the regression is in the form of a panel that covers consumptive water use by power plant for the years from 1993 to 2016. Three types of data were needed, those on water use, those on climate and those on power plant characteristics. The water use data were obtained from the TWDB water use and planning data group. The climate data used involves ambient temperature and precipitation and for that we used the monthly mean temperature and precipitation within the county where the power plant operates, that were obtained from the

PRISM Climate Group (PRISM 2018). The power plant characteristic data were drawn from EIA Form 860 and Form 923. The data used give capacity and monthly generation along with type of power plant. The plant types used include coal fired plant, natural gas steam turbine plant (NGST), natural gas combustion turbine plant (NGGT), natural gas combined cycle plant (NGCC), and petroleum plant. We report summary statistics on the data in Table 3.1.

Table 3.1 Summary statistics

Variable	Obs	Mean	Std.Dev.	Min	Max	Skewness
Generation (MWh)	1,096	126,097.0	143,748.0	148.0	601,034.0	0.7
Capacity (MW)	1,096	326.0	267.0	40.0	1,088.0	0.7
Consumption(gallons)	1,096	180,080,308.0	203,584,414.0	545,184.0	768,473,720.0	1.3
Temp(°C)	1,096	22.0	6.5	8.5	32.0	-0.3
Prep(mm)	1,096	68.5	67.1	0.0	500.6	1.8

To estimate climate impacts on power plant generation, we use the following linear functional form:

$$(3.1)\quad log(Generation)_{it} = b_1 + b_2 Temp_{it} + b_3 Prep_{it} + b_4\, log(Capcity)_{it} + \beta_i + \mu_{it}$$
$$where\ i = plant, t = month\ in\ 1993\ to\ 2016$$

Here $log(\,Generation)$ is a log transformation of monthly power plant generation for plant i in month t, $Temp$ is the mean temperature in month t at location i, $Prep$ is the mean monthly precipitation during month t at location i, $log(\,Capacity\,)$ is the log transformation of power plant capacity during that month at that plant, β_i is a time invariant unobserved individual effect at plant i, $\mu_{it}$is an error term that is assumed to be normally distributed with zero mean. The log transformation is used since it is a good way to transform a skewed variable into one that is more approximately normal (Benoit 2011). Also, it reduces the variability of the raw data.

Given the above function we also estimate a regression function for water consumption as below:

$$(3.2) \qquad log(Consumption)_{it} = a_1 + a_2 Temp_{it} + a_3 Prep_{it} + a_4\, log(Capacity)_{it} + a_5\, log(Generation)_{it} + \alpha_i + \epsilon_{it}$$

$$where\ i = plant, t = month\ in\ 1993\ to\ 2016$$

Here much of the notation is as defined above. New items here are $log(Consumption)$ which denotes the log of the consumptive water use for power plant i during month t, α_i is the individual effect of plant i, $\epsilon_{it}$is an error term that is again assumed to be normally distributed with zero mean.

Using equations (3.1) and (3.2), the total temperature effect on consumptive water use involves the direct temperature impact on consumptive water use plus the indirect effect of temperature on generation and then the effect of generation on consumptive water use. In particular, if we use f to denote the log consumptive water use function and g to denote the log generation function, then we have the following total temperature effect on the log of consumptive water use:

$$(3.3) \qquad \frac{\Delta log(Consumption)}{\Delta Temp} = \frac{\Delta \hat{f}}{\Delta Temp} + \frac{\Delta \hat{f}}{\Delta log(Generation)} * \frac{\Delta \hat{g}}{\Delta Temp}$$

where $\frac{\Delta \hat{f}}{\Delta Temp}$ is the direct temperature impact on log consumptive water use, and $\frac{\Delta \hat{f}}{\Delta\, log(Generation)} * \frac{\Delta \hat{g}}{\Delta Temp}$ is the indirect effect of temperature on log consumptive water use. With the estimation results, we know that the marginal effect of temperature on log consumptive water use is: $\frac{\Delta log(Consumption)}{\Delta Temp} = \hat{a}_2 + \hat{a}_5\hat{b}_2$, in terms of consumptive water use itself, we expect an $(\exp(\hat{a}_2 + \hat{a}_5\hat{b}_2) - 1) * 100$ percent increase in the consumptive water use. Similar to the total temperature effect on log consumptive water use, the marginal effect of precipitation on log consumptive water use is: $\frac{\Delta log(Consumption)}{\Delta Prep} = \hat{a}_3 + \hat{a}_5\hat{b}_3$.

Since equation (3.1) and equation (3.2) have the same regressors, $log(Capacity)$, $Temp$, $Prep$, and $log(Generation)$ also enter as regressors in equation (3.2), the error terms μ_{it} and ϵ_{it} will be highly correlated. Thus, we estimate the equations as a system. We first transform the equations to reduced form, which is shown in equation (3.4), where η_{it} is the linear combination of μ_{it} and ϵ_{it}. Then we estimate the equations in a system to get the marginal effect of climate on consumptive water use.

$$(3.4)\begin{cases} log(Consumption)_{it} = (a_1 + a_5b_1) + (a_2 + a_5b_2) * Temp_{it} + (a_3 + a_5b_3) * Prep_{it} \\ \qquad + (a_4 + a_5b_4) * log(Capacity)_{it} + (\alpha_i + a_5\beta_i) + \eta_{it} \\ log(Generation)_{it} = b_1 + b_2Temp_{it} + b_3Prep_{it} + b_4\,log(Capacity)_{it} + \alpha_i + \mu_{it} \end{cases}$$

To do this we use seemingly unrelated regression (SUR) to control for the fact that the error terms in equations (3.1) and (3.2) are correlated. In particular, use of SUR can help gain efficiency in estimation by combining information on several equations(Moon and Perron 2006). With the reduced form equation (3.4), we can estimate the equations simultaneously and get the total marginal effect of climate on consumptive water use.

3.6.2. Water Usage Results

Table 3.2 shows the estimation results. In terms of climate, the direct marginal effect of temperature on $log(Consumption)$ is significant and equals 0.0155, and the indirect marginal effect of temperature on $log(Consumption)$ is significant and equals 0.0342. Combining these the total marginal effect of temperature on log water consumptive use is 0.0497 or 1.05 gallons per degree centigrade increases. In terms of percentage change at the mean in the original units, we expect a significant 5.1% increase in consumptive water use with a unit increase in temperature. For the precipitation, the total marginal effect of precipitation on log water consumptive use is -0.0009, we expect a 0.09% decrease in consumptive water use in gallons with a unit increase in precipitation in millimeter.

Table 3.2 Econometric results of log water consumption regressions

	$log(Generation)$	$log(Consumption)$
Temp(°C)	0.0349***	0.0155***
	(0.0030)	(0.0020)
Prep(mm)	-0.0008**	-0.0005**
	(0.0003)	(0.0002)
$log(Capacity)$ (MW)	1.2143***	-0.6304***
	(0.0812)	(0.0561)
$log(Generation)$(MWh)		0.5357***
		(0.0191)
Constant	1.1081*	14.2571***
	(0.4783)	(0.3018)
R squared	0.9029	0.9621
Obs	1096	1096
RMSE	0.6222	0.3813

Note: values in parentheses are standard errors with * for $p<0.05$, ** for $p <0.01$, and *** for $p <0.001$, respectively.

3.7. Cooling Retrofit Use and Water Yield Cost Estimation

The costs of changing cooling systems are estimated using the Integrated Environment Control Model (IECM) (Rubin, Berkenpas and Zaremsky 2007) after adapting the data in that model to South Central Texas. We assume the life of the cooling system in a power plant is 30 years, and the discount rate is 6.0%. IECM provides estimates of capital and altered operation and maintenance (O&M) costs associated with the altered cooling system.

We also needed to compute the cost of water saved (CWS) when retrofitting cooling systems. This involved dividing retrofit cost by water savings. The water savings is the difference in consumptive water use before and after the retrofit. The cost change involves the change in capital and operation and maintenance cost plus any lost revenue from reductions in electricity generated. The resultant formula is:

$$(3.5)\ CWS = \frac{Capital\ cost + \Delta\ O\&M - Electricity\ price * \Delta Net\ generation}{\Delta Water\ use}$$

where capital cost is the annualized cost incurred when retrofitting the cooling method; Δ O&M is the difference in annual O&M costs with and without the cooling retrofit; electricity price is the wholesale electricity price per MWh reported by each power plant; ΔNet generation is the changes in annual net electricity generation in MWh that occurs when retrofitting the cooling system and is negative when generation is reduced; ΔWater use is the change in annual water consumption in acre-feet resulting from the cooling retrofit.

Under drought condition, ΔWater use is expected to increase. As shown in Table 3.2, the sign for temperature is positive, and the sign for precipitation is negative, indicating that water saved through retrofitting recirculating cooling systems to dry cooling systems is greater in drier condition compared to normal state.

3.8. Results and Analysis

Here we primarily focus on transitions from recirculating to dry cooling since recirculating cooling is the predominant method in current use.

3.8.1. Cost of Adopting Alternative Cooling in Existing Plants

Table 3.3 displays the per acre-foot cost by plant after applying equation (3.5). Note in looking at these results that broad assumptions were used on cost across plants and this analysis did not consider the detailed specifics of technical feasibility within a plant, and for some cases the retrofit may not be possible because of limited land space or other technical factors.

Water saving with the dry cooling retrofit (DCR) in Table 3.3 is estimated by using the predicted water consumption as estimated in the SUR model for the current plant configuration versus that for a dry cooling plant. In projecting consumption, we use local climate conditions in the county where the plant exists and use the plant specific data on capacity, fuel type and generation activity. In turn, the estimated total annual water saving when converting from recirculating to dry cooling in the region is 60,307 acre-feet for the aggregate of all regional plants.

The computations show the average retrofit cost per acre-foot of water saved is $9,315 per acre-foot. Overall, the estimated average cost of retrofitting cooling systems of existing power plants is higher than the TWDB estimated costs for water projects. There are two utilities in Table 3.3 have computed retrofit costs of over $30,000/acre-foot, due to low consumptive use estimates in the TWDB survey coupled with a high cost estimate. We find refineries have lower retrofitted cost than that in traditional electric utilities, due to lower capacity of power generation in these refineries, which yields lower capital cost in installing cooling systems and also lowers operating cost.

Table 3.3 Consumptive water saving and retrofit cost

Plant Name	Type	Average generation	Capital cost	O&M cost	Lost in generation revenue	Change in cost	Annual water savings	Retrofit cost
PERSALL PLANT	NGST	47	4303	732	157	5192	128	40437
RIO NOGALES POWER PLANT	NGCC	2144	11090	1083	210	14271	1573	9071
SAN MIGUEL ELECTRIC CO OP	COAL	2642	27970	2445	126	31672	6200	5108
CORPUS CHRISTI COGENERATION	NGCC	2380	12280	1147	211	15540	10925	1422
VALERO REFINING TEXAS LP - WEST PLANT	PETROLEUM	301	2396	406	143	2945	7084	416
VALERO REFINING TEXAS LP - EAST PLANT	NGGT	221	1282	213	143	1639	2794	587
CORPUS REFINERY	NGGT	276	973	91	239	1304	6141	212
FORMOSA PLASTICS CORPORATION USA	NGCC	3975	12280	1331	248	1610	21798	738
GUADALUPE POWER PARTNERS	NGCC	5661	13100	1197	212	1642	3435	4780
LEON CREEK POWER PLANT	NGGT	85	6042	817	83	6942	229	30377

Note: the unit of average generation is in 10^3mw; capital cost is in 10^3\$; O&M cost is in 10^3\$; lost in generation revenue is in 10^3\$; change in cost is in 10^3\$; annual water saving is in acre-feet; retrofit cost in $/acft.

3.8.2. Cost of Adopting Alternative Cooling in New Plants

The region is adding new power plants and here we consider use of dry cooling as opposed to recirculating cooling methods. Here the cost may be lowered as one just needs the new investment and does not need to remove old equipment or manipulate the existing system to accommodate new equipment. Regionally new NGCC plants are being built in Nueces, Victoria, and Bexar Counties. We compute the water savings cost for conversions to dry cooling for five different levels of plant capacity by county (Table 3.4). The cost of water saving is estimated by the cost difference between installing and operating the two cooling systems including changes in generation revenue divided by the water saved. The results show the cost of water consumption saved by using dry cooling at the new NGCC plants are lower compared to that for existing plants.

Table 3.4 Cost of water consumption saved with DCR for new NGCC plants

New plant location	Capacity	Change in cooling system install cost	Change in O&M cost	Change in generation revenue	Retrofit cost	Water saved
Calhoun	285	2675	820	714	492	8552
Nueces	285	2675	820	714	473	8892
Bexar	285	2675	820	714	502	8392
Calhoun	570	5321	1122	1250	574	13410
Nueces	570	5321	1122	1250	552	13942
Bexar	570	5321	1122	1250	585	13159
Calhoun	854	7995	1428	2142	662	17463
Nueces	854	7995	1428	2142	637	18157
Bexar	854	7995	1428	2142	675	17137
Calhoun	1140	10714	1744	3035	735	21085
Nueces	1140	10714	1744	3035	707	21922
Bexar	1140	10714	1744	3035	749	20690
Calhoun	1424	13531	2079	3927	801	24376
Nueces	1424	13531	2079	3927	771	25344

Table 3.4 Continued

New plant location	Capacity	Change in cooling system install cost	Change in O&M cost	Change in generation revenue	Retrofit cost	Water saved
Bexar	1424	13531	2079	3927	817	23920

Note: the unit of capacity is in mw; change in cooling system install cost is in 10^3\$; change in O&M cost is in 10^3\$; change in generation revenue is in 10^3\$; retrofit cost is in \$/acft; water saved is in acft

3.8.3. Comparison with TWDB Water Projects

To examine the cost competitiveness of these cooling system retrofits we compared their costs with those for water management strategies proposed in the 2016 TWDB Region L and Region N Water Plans. The TWDB regional strategies focus on several major categories of actions including municipal conservation, new ground water sources, aquifer storage and recovery (ASR), new surface water sources, out of region water sources, reuse, and use of new off-channel reservoirs. For each project, the regional planning group estimated the amortized capital cost; the fixed operating cost per unit of water yield; the variable operating cost per unit of water yield (summing water purchase fee, ground water district export fee, and pumping energy cost).

We show the costs for 59 regional TWDB water projects in Figure 3.1 with triangles giving the costs of power plant retrofits and new installations. There we see that municipal conservation projects have the lowest estimated average cost per unit of water saving - about \$589/acre-foot on average. On the other hand, projects importing water from other regions are more expensive, due to the high capital cost of constructing pipeline systems to transport water. For example, the Vista Ridge project would build a 143-mile-long pipeline to transport groundwater from Burleson County to San Antonio at an estimated cost of \$1,976/acre-feet.

Another project using seawater desalination coupled with a pipeline to move the water to the San Antonio region yields a cost of $2,713/acre-foot.

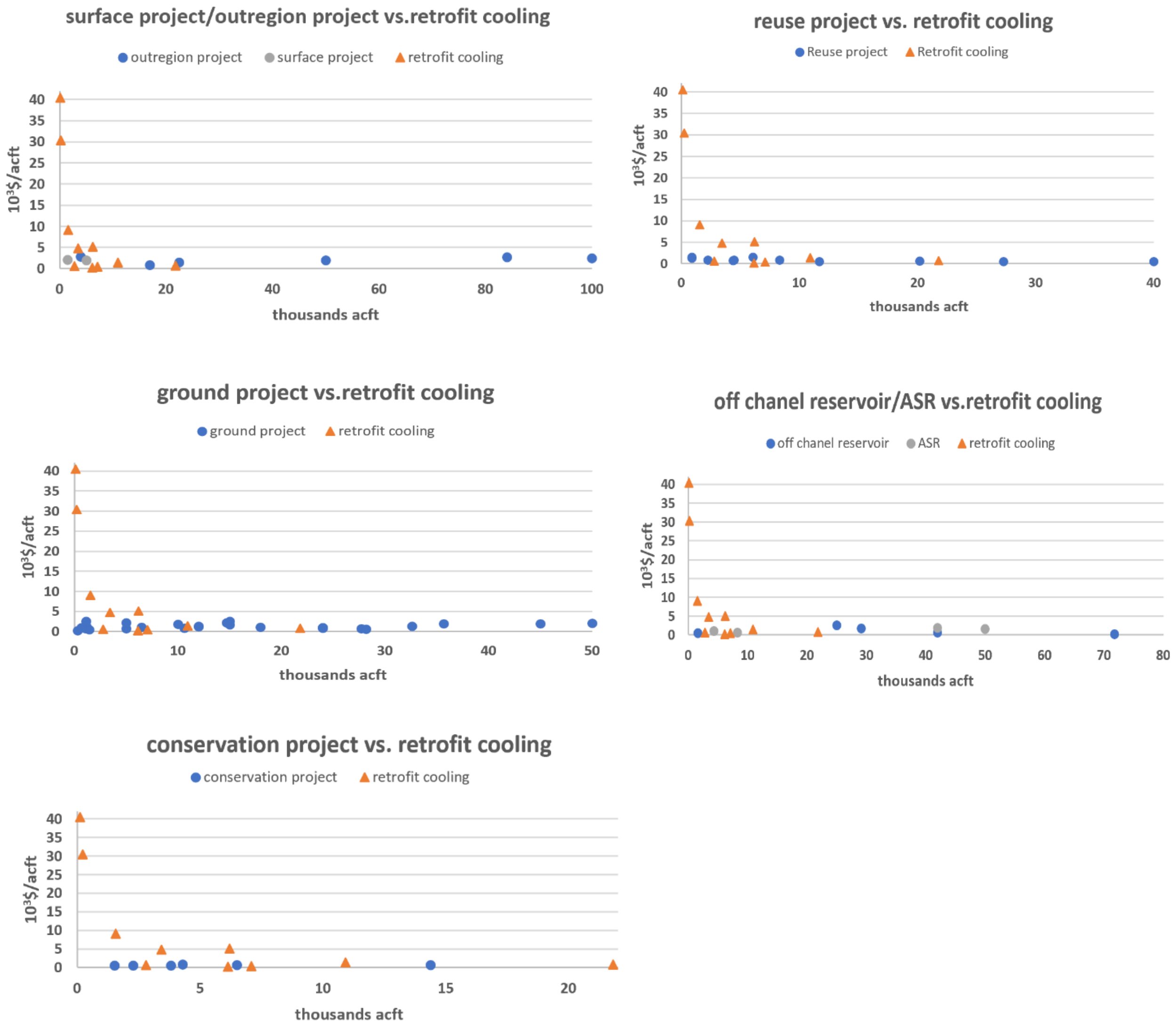


Figure 3.1 Comparison between cooling retrofit cost and unit cost of TWDB water projects

Overall, the average cost of DCR is estimated to be $9,315/acre-foot, comparison shows that this is generally more expensive than most TWDB water projects. However, a few retrofits were cost competitive. Most of the ground water projects have lower unit cost than the retrofits, however, the brackish ground water projects are more expensive than some retrofits. For example, Schertz-Seguin Water Supply Corporation is planning to use brackish Wilcox ground water at a unit cost of $2,554 /acre-foot, which exceeds the dry cooling retrofit cost at 5 power plants. Additionally, there are 5 power plant retrofits with lower costs of water saving than the TWDB out of region water import projects. Table 3.5 displays the average unit cost, the minimum unit cost, the maximum unit cost of TWDB water projects and power plant dry cooling option. The minimum and maximum columns describe the cheapest and the most expensive cost of retrofitting individual plant or a specific TWDB water project.

Table 3.5 Comparison between the cost of DCR and TWDB water projects

	Water Saving Strategies	Average Cost ($/acft)	Min Cost ($/acft)	Max Cost ($/acft)
TWDB Water Project	Municipal Conservation	589	470	770
	Reuse Projects	749	458	1500
	Ground Water Projects	1285	135	2554
	Surface Water Projects	1979	1886	2072
	Off-Channel Reservoir	1091	140	2561
	Aquifer Storage and Recovery	1286	585	1835
	Other Water Projects	2034	867	2803
Cooling Retrofit	Existing Recirculating to Dry	9315	212	40437
	New NGCC Recirculating to Dry	649	473	817

3.8.4. Cost of Adopting Alternative Cooling under Climate Change

When climate change is factored in, cooling water consumption increases. We estimated water consumption in 2050 and 2090 under four emission scenarios, i.e. RCP 2.6, 4.5, 6.0, and 8.5. For each emission scenario, we use the monthly mean temperature and precipitation from the Global Circulation Model IPSL-CM5A-LR in 2050 and 2090. Table 3.6 displays the percentage change in projected temperature and precipitation in the region where power plants are located, we use climate in current condition as baseline. Temperature increases in 2050 under four emission scenarios and further increases in 2090, whereas precipitation decreases, indicating drier condition in the projection period.

Table 3.6 Projected climate change in the region

	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Temperature %change				
2050	4.45	7.60	7.19	10.89
2090	3.11	9.09	10.38	25.50
Precipitation %change				
2050	-24.16	-35.95	-43.46	-26.56
2090	-25.44	-32.90	-16.60	-39.91

Figure 3.2 displays the SWAT output of climate change impact on the net inflow of two major cooling diversion points. These two cooling diverters are located on the lower stream of Nueces River, and net inflows are projected using IPSL-CM5A-LR climate model under extreme RCP (8.5) in 2050 and 2090. Net inflow changes shown in Figure 3.2 are based on volumes relative to the level in current climate condition. Under climate change condition, net inflow generally increases in the winter and decreases in the summer, indicating that less available river flow during summer may increases the possibility of drought condition in the projection period.

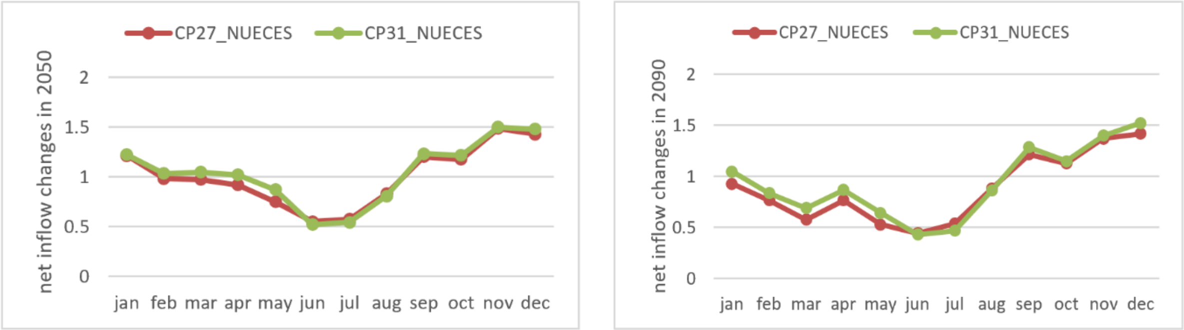


Figure 3.2 Net inflow changes in 2050 and 2090

Figure 3.3 displays the estimated total water use for all the plants in South Central Texas under each RCP scenario respectively. For example, under RCP 8.5 scenario, there is a 19.7 % increase in water consumption in 2050 relative to the base year, and a 33 % increase in 2090 relative to the base year. Across all the climate scenarios the total water use increase, water consumption under RCP8.5 increases more than other climate scenarios.

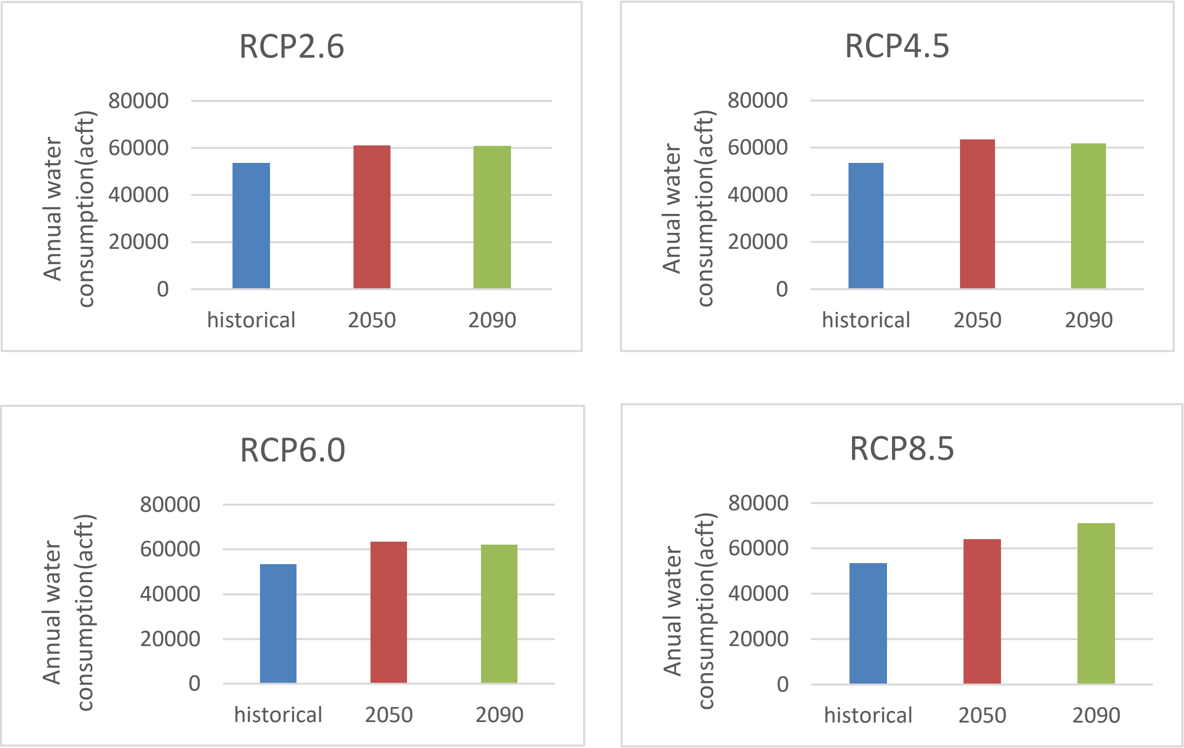


Figure 3.3 Water consumption under climate change scenarios

We also compared the cost of cooling system retrofit under the RCP 8.5 climate scenario with TWDB projects under the assumption of no cost increase in cooling installation and no cost effects on the TWDB projects (see the Appendix A to H, a complete list of water saving and the retrofit cost under each climate scenario). Under the RCP 8.5 scenario in 2090, 5 power plants have lower cost than some of the out of region water supply projects and ground water supply projects, 5 plants have lower cost than some of the off-channel reservoir projects.

Nonetheless, the majority of TWDB projects are less expensive, one other factor may stimulate retrofits. Namely cooling system retrofits may be justifiable on a reliability basis as surface water supplies are expected to decline (Seager et al. 2013), and that may stimulate the conversion of cooling systems.

3.9. Conclusion

Cooling retrofits can reduce water use. The cost estimates developed herein show in most cases cooling changes are expensive ways of saving water. In particular, costs per acre foot of water saved for retrofitting existing recirculating cooling systems to dry cooling systems were found to have an average estimated cost of about $9,315 per acre-foot of water saved. This cost is higher than most of the regional TWDB water development possibilities, only being competitive with the cost of the high end TWDB projects. We also found the estimated costs for installing dry cooling in new NGCC power plants were lower exhibiting a range of cost of water saved between $473 per acre-foot and $817 per acre-foot. Retrofitting once-through cooling systems to recirculating cooling systems is not cost effective since consumptive water use in fact increases in recirculating cooling systems.

Finally, when considering climate change, we estimate that climate change effects cause increases in consumptive water use for the systems being replaced in turn increasing the water savings from an action and as a result the cost of DCR is lower. There may be a reason to covert cooling in the future but the retrofits are still expensive ways of saving water. It appears that the retrofits will more likely be considered as means of increasing reliability accommodating reductions and needs to expand water use.

4. EFFECTS OF POPULATION GROWTH AND CLIMATE CHANGE ON FEW ACTIVITY BY THE ELECTRICAL ENERGY SECTOR: A CASE STUDY IN SOUTH CENTRAL TEXAS

4.1. Introduction

In the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), there is a projection that global surface temperature will increase between 1.5°C and 4°C by 2100, depending on climate scenario(Pachauri et al. 2014). Cook, Ault and Smerdon (2015) use an empirical drought index and soil moisture metrics for the Central Plains and Southwest in the US from the 17 GCMs used in that projection, and show consistent drying during the later half of the 21st century. As a result, climate change incidence is likely to affect many water-related activities, from agricultural production, to municipal and industrial water supply, including electrical power plant cooling and generation. Meanwhile, growing populations further increases FEW commodity demands. Collectively, such developments raise needs for combined climate change and population change analyses.

This chapter focuses on a Texas based case study on the effects of population growth and climate change on the electricity sector in terms of demand, cooling water use for power plants, power plant capacity, power plant construction, retrofits of boiler and cooling systems, and welfare. It is likely that climate change and growing population will make existing regional water scarcity even worse, thus we examine how cooling and capacity expansion decisions are made in energy sector to improve regional welfare.

This chapter is organized as follows. Section 4.2 provides some background information about FEW Nexus modeling. Section 4.3 describes the characteristics of the model used in the empirical analysis. Section 4.4 discusses data for the model. Section 4.5 specifies the model structure used in this study, and also presents algebraic equations. Section 4.6 displays model results and discussions under different scenarios. Finally, we summarize key findings and decision implications.

4.2. Literature Review on FEW model

FEW Nexus analysis is relatively new, although components have been analyzed for years. Often such analyses are not comprehensive across all FEW sectors nor are they integrated into a simultaneous total FEW system. We reviewed FEW related concepts in the second chapter, now we introduce analyses and models that address part or all of FEW Nexus elements.

Agricultural sector and market models such as FASOM (Beach and McCarl 2010) simulate production, processing, transporting and marketing in the US agricultural sector. FASOM has been widely use in examining the impact of external forces on crop mix and productivity, bioenergy, livestock productivity, land conversion, and greenhouse gas emission reductions(Adams et al. 1990; Murray et al. 2005;Mu, McCarl and Wein 2013; Attavanich et al. 2013; Fei, McCarl and Thayer 2017).

Hydrology models are also a family of models used to address FEW Nexus issues. The Soil & Water Assessment Tool (SWAT) (Arnold et al. 2012) is a river basin scale model and is designed to predict the impact of land use and management scenarios on water flows, sediment, and agricultural chemical fate. Major model components include weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria, pathogens, and land condition. Groundwater Availability Model (GAM) models aquifers, examining the effects of items like recharge; geology; rivers, lakes, and springs; water levels; aquifer properties; and pumping diversions.

There are different types of energy models, such as energy planning models, energy supply-demand models, forecasting models, renewable energy models, emission reduction models and optimization models. Energy Portfolio Assessment Tool (EPAT) is a scenario-based tool that enables the policy maker to create an energy portfolio scenario using various energy and electricity sources. It then evaluates the environmental and economic sustainability of the scenario. Mroue et al.(2019) assess energy portfolio scenarios for Texas as set by EIA Clean Power Plan, and find Clean Power Plan succeeds in mitigating carbon emissions and decreasing water withdrawals, it also increases water consumption in electricity generation and significantly increases land use.

In addition, we reviewed optimization models for the purpose of this study. MARKAL(Fishbone and Abilock 1981) depicts both the supply and demand sides of the energy system. The model uses linear optimization techniques to generate an energy supply system that meets demands. The model covers the entire energy system – from energy resources to end uses through energy conversion processes. The demand side of the model uses exogenous assumptions about demand drivers and the elasticities of demand with respect to these drivers and prices. The supply side consists of a set of supply curves representing the potential available resources. The model seeks to optimize the total welfare (consumers' and producers' surplus) and simulates a partial equilibrium solution. The model is a multi-period model that can be applied to a large number of regions and can capture trading options.

Tools for Energy Model Optimization and Analysis (Temoa) (DeCarolis, Hunter and Sreepathi 2010) is also an energy system optimization model. Temoa is formulated as a linear program that minimizes the total system cost of energy supply by optimizing the installation of new capacity and utilizing both new and existing capacity to meet demand. Constraints include conservation of energy at the individual process level, the global balance of commodity production and consumption, the satisfaction of end-use demands, emission limits, maximum technology growth rates, and bounds on technology capacity and activity.

The model developed in this study is based on several previous studies have been done in the Edwards Aquifer. The EDSIM model is an economic and hydrological simulation model that depicts water allocation, agriculture, municipal/industrial use, springflow and pumping lifts (McCarl et al. 1999). The EDSIM was developed in a series of studies by Dillon et al. (1993), Lacewell and McCarl (1995), Keplinger (1998) and Williams (1996). The EDSIMR (Gillig, McCarl and Boadu 2001) is an extension that incorporates the interaction between surface water and ground water in the Edwards Aquifer region. The RIVERSIM developed by Cai (2009) further expanded the model scope to surface water statewide.

The Edwards Aquifer model optimizes consumers' and producers' surplus by simulating the allocation of resources in a perfectly competitive economy (McCarl and Spreen 1980; Lambert et al. 1995). This model has been used to study dry year irrigation suspension (Keplinger et al. 1998), climate change effects (Chen, Gillig and McCarl 2001), regional water planning (Gillig, McCarl and Boadu 2001), El Niño-Southern Oscillation (ENSO) effects (Chen et al. 2005b), and elevation dependent management (Chen, McCarl and Williams 2006). Ding (2014) further expanded EDSIM by adding livestock production; land conversion from irrigated or dryland to pasture land; and increased probabilities of drought occurrences.

To date the previous models have not covered the energy component in interactions with water. Namely, the model has omitted electric power generation and cooling water. Few if any works were found to examine the electrical power cooling in the context of the full FEW Nexus. This chapter reports on a study that incorporates electric power generation with the consideration of food production, surface and groundwater supply, and water development projects.

4.3. Model Characteristics

The FEW Nexus model (EDSIMRGW_NEX) used in this study is based on developments in RIVERSIM, EDSIMR and Dings' version of EDSIM (see model development and structure for details(Fei, Yang and McCarl 2019)). EDSIMRGW_NEX includes surface water flows and aquifer interactions in South Central Texas; crop and livestock production; water management strategies proposed by TWDB; electric power generation and cooling system water usage; climate change and population growth demand expansions for FEW components.

EDSIMRGW_NEX is implemented as a two-stage stochastic, mixed integer programming model which covers all FEW Nexus sectors. The two stages in the model depict the uncertainty inherent in regional water supplies including recharge plus involved demand modifications. EDSIMRGW_NEX operates across 9 states of nature ranging from very dry to very wet years. In the first stage, the crop mix and livestock mix, land conversion, major water projects, retrofits and new power plants are decided independent of specific weather and recharge uncertainties other than their long run distribution. Then, in the second stage, irrigation strategy, power generation, municipal use and water project utilization is decided with knowledge of recharge and pumping lift. In particular, land conversion only occurs in the first stage and is constant across all states of nature. Water use in municipal and industrial sectors depends on state of nature conditions. The volume of Edwards Aquifer springflow and elevation are highly affected by recharge level and water usage by agricultural and non-agricultural sectors. Decisions such as whether to build a water project, retrofit the cooling systems or boiler of power plant, and build a new power plant are also made in the first stage, while decisions of whether to operate power plant, electricity demand, and fuel consumption are dependent on state of nature.

The scenarios in EDSIMRGW_NEX are set up as a recursive programming model. Basically, recursive programming models involve problems in which model coefficients are functionally dependent upon earlier model solutions and an exogenously specified time path. Following Day(1978), a recursive programming model consists of a constrained optimization model; and a data generator. For example, the data generator given the solution in the year 2015, prepares the input, such as end lift level, water project operation level for the projection year 2030. The parameters are updated in the recursive process, municipal and industrial water demand are adjusted by population growth; electricity demand is updated when population growth and climate change effect factor in; crop yield and water use is estimated by Blaney Criddle(BC) procedure(Pruitt and Doorenbos 1977), in particular, the BC procedure is used to alter yields and water use for the projected climate change scenarios in the EDSIMRGW_NEX; livestock budget and stocking rate are updated under each projection period and climate scenario; climate effects on inflow are updated by using SWAT model; we use estimated regression coefficients to calculate the effects of maximum temperature and precipitation on aquifer recharge under each projection period and climate scenario. While variables are also updated in the recursive process, available land, ending elevation of aquifers, existing water projects, existing power plants, and retrofitted plants are solved in the current period, and then feed into the next period as initial values. The model then is optimized for each time period with the data generator updating the model to the next time period.

According to expert opinion (Dr. John Nielsen-Gammon, Texas A&M University), the best fitting General Circulation Models (GCMs) for Texas are BCC-CSM-1, GFDL-ESM2M, IPSL-CM5A-LR, MIROC5, MRI-CGCM3, and NORESM1-M. Among them we use MIROC5[1] and IPSL-CM5A-LR[2] in the empirical model. MIRCO5 projections show a relatively wetter future and IPSL-CM5A-LR show a drier one. These two GCMs are run under 4 RCP (2.6,4.5,6.0 and 8.5) scenarios used in IPCC AR5 (Pachauri et al. 2014). Table 4.1 displays the resultant projected percentage change in temperature from 2030 to 2090. Table 4.2 displays the percentage change in precipitation from 2030 to 2090. We averaged the monthly temperature and precipitation from 1981 to 2016 in the study region, and the mean value is used as baseline. MIROC5 yields less temperature change than does IPSL-CM5A-LR. In terms of RCP scenarios, the RCP8.5 has the highest increase in temperature while the RCP2.6 has the lowest, which is consistent with the GHG concentration and radiative forcing assumptions inherent in the RCPs. Precipitation is more variable and may rise or decline in IPSL-GM5A-LR and MIRCO5 models, we can see from Table 4.2 that MIROC5 yields more precipitation than IPSL-GM5A-LR in most cases.

Table 4.1 Temperature changes in the study region

GCMS	RCP	2030	2050	2070	2090
IPSL-CM5A-LR	RCP2.6	7.54%	8.30%	7.19%	6.84%
	RCP4.5	10.01%	11.67%	12.55%	13.49%
	RCP6.0	6.16%	11.47%	11.88%	14.81%
	RCP8.5	7.18%	15.22%	21.81%	31.02%
MIROC5	RCP2.6	6.75%	6.44%	6.70%	7.25%
	RCP4.5	8.08%	10.41%	10.94%	12.72%
	RCP6.0	4.83%	8.74%	11.21%	13.24%
	RCP8.5	8.00%	13.31%	18.96%	23.89%

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[1] MIROC5 is developed by University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology.

[2] IPSL-CM5A-LR is developed by Institute Pierre Simon Laplace.

Table 4.2 Precipitation changes in the study region

GCMS	RCP	2030	2050	2070	2090
IPSL-CM5A-LR	RCP2.6	-4.24%	-0.26%	-6.06%	-2.92%
	RCP4.5	-13.27%	-14.83%	-11.31%	-11.77%
	RCP6.0	0.22%	-23.70%	3.62%	5.79%
	RCP8.5	12.86%	-4.53%	-17.82%	-24.02%
MIROC5	RCP2.6	-9.33%	20.81%	17.51%	7.13%
	RCP4.5	1.11%	17.26%	5.65%	13.86%
	RCP6.0	8.50%	2.16%	15.47%	3.44%
	RCP8.5	13.32%	-1.07%	-10.53%	2.86%

4.4. Data

We briefly describe FEW Nexus data here (see Fei et al. (2019); Fei (2019) for details). EDSIMRGW_NEX is developing using data from various sources. EDSIMRGW_NEX includes data across all FEW sectors. The agricultural data include: crop and livestock budgets, historical crop and livestock mixes, available agricultural land, land rents, and alternative dryland and irrigation cropping strategies. Water component data include: water use and return flow for major diverters including cooling water for power plants, agricultural producer water sources and irrigation needs, municipal and industrial water demands; groundwater aquifer elevation, pumping and recharge and aquifer response functions given net discharge; and TWDB proposed water projects. Energy data include: power plant capacity, capacity factor, heat rate; annualized capital and OM cost; cooling water use; and regional per capita electricity demand. In addition, population location and projected growth, and climate change effects are incorporated.

4.5. EDSIMRGW_NEX Model Structure

Here we focus on changes in model structure involved with adding the energy component. The objective function maximizes the expected net benefits by water use sectors, assuming the allocation of resources in a perfectly competitive economy. In particular, to conduct our research, the following modifications are made:

(1) We introduce an explicit demand curve for electricity, assuming demand for electricity has constant price elasticity. Given this assumption, electricity price will approach infinity when demand is close to zero, yielding a very large area when computing consumers' welfare. Thus, it can generate an extremely large value for the objective function, especially when the demand curve is inelastic as the curve is asymptotic to the axis. Consequently, following procedures in FASOM (Adams et al. 2005) the curve is truncated at 1/3 of the projected level of demand. In particular, optimal electricity demand is less or equal to 1/3 of the projected level, the marginal benefit is assumed to be fixed at the marginal benefit corresponding to 1/3 of projected electricity demand. Also following FASOM, this nonlinear benefit function for electricity demand is approximated in stepwise form using a separable programming. Fifty-four points spanning the projected level are used to approximate the optimal electricity demand.

(2) We add electrical cooling and boiler retrofit options, i.e. retrofitting cooling systems and boilers of power plants. These decisions – whether or not retrofits should be adopted – are depicted as integer variable choices, with amortized fixed cost and capacities involved. The amortized fixed cost of each retrofit is entered in the objective function and becomes active only if the associated integer variable in one depicting the situation where that retrofit is implemented. The model also depicts variable costs that depend on the amount of electricity generated and are only

incurred when the retrofit is implemented. The amount of electricity can be generated from retrofitting the cooling system or the boiler is limited by the capacity of each power plant and the characteristics of the retrofit.

(3) This study also adds the possibility of building new power plants in the region, i.e. new NGCC, solar and wind power plants. For new NGCC, we include different capacities of NGCC and associated costs plus cooling alternatives. For the potential wind and solar renewable power plants, we add cost and location-specific capacity information, the specification is based on the Regional Energy Deployment System (ReEDS) model (Eurek et al. 2016), which categorizes renewable power plant potential by location based on radiation for solar and wind speed for wind plant.

(4) We assume a current electricity gap in the region as the region imports electricity from other regions. Electric power flows among counties are included in the transmission balance, and transmission loss depends on the distance between counties.

The objective function has state of nature independent and probabilistically weighted state of nature dependent terms. The terms cover benefits and costs for each sector as described below. In our presentation variables will be typed in upper case and parameters in lower case. The principal terms in the equation below are:

- Net benefit to municipal and industrial water use. This involves the area under municipal and industrial demand curves and subtracts off municipal and industrial water cost using surface water ($SURFACEDIVERSION$) summed across each river (r), riverplace (rp), county (c), sector type (s) in month (m) under state of nature (son); pumping cost using groundwater ($PUMPGROUND$) by each aquifer (a), layer (l), county (c), type (s) in month (m) under state of nature (son); and pumping cost using minor aquifers ($OTHERAQUIFER$) by each county (c), sector type (s) in month (m) under state of nature (son).

- Net revenue in the agricultural sector. This includes net income derived from irrigated and dryland crop production added to that from livestock production. The crop profit is the crop revenue minus production cost times acres produced ($CROPACRE$) summed across each county (c), zone (z), crop (cr), land irrigation type (ir), and state of nature (son). The livestock profit is the livestock revenue minus production costs per animal unit by county (c), livestock (ls), feeding method (f), and state of nature (son), and times quantity of livestock ($LIVEPROD$) raised. We then subtract water costs for agricultural pumping from groundwater, surface, and minor aquifers. Land transfer ($LANDTRANSFER$) costs are also included consisting of both the costs of land transfer from furrow to sprinkler irrigation and land use change.
- Net benefit from mining (fracking) water use, which is the mining water revenue from leasing water minus the pumping cost from aquifers, surface water, and minor aquifers.
- Net benefits of recreation and other sectors.
- Value of water escaping to bay is also included to give an instream flow value.
- Costs of major regional water projects are treated. This includes the investment costs which are the fixed cost associated with each water project (wp) times the integer variable indicating if that water project is built ($DO\_I\_BUILD\_WATER$). The model also includes the operating costs which are the amount of water used ($PROJECTWATER$) times the cost per unit.

- Net benefit of electricity sector. This involves the area under electricity demand curve minus cost of operating and retrofitting power plant, which includes fixed cost of retrofitting cooling systems, and boiler systems plus the fixed cost of building new power plants (new NGCC, new wind and solar generation-based plants). Next, we include the operating and maintenance cost for generation (both thermal electric plants and renewable plants), fuel and cooling water for thermal plants and a penalty for once-through cooling systems.

$$
\left.\begin{aligned}
&\sum\nolimits_{son} prob_{son} * \{+\sum\nolimits_{a,l,c,m}(\int gmundem_{a,l,c,\text{"mun"},m,son}\left(PUMPGROUND_{a,l,c,\text{"mun"},m,son}\right)dPUMPGROUND_{a,l,c,\text{"mun"},m,son} + \\
&\qquad\qquad\qquad \int ginddem_{a,l,c,\text{"ind"},m,son}(PUMPGROUND_{a,l,c,\text{"ind"},m,son})dPUMPGROUND_{a,l,c,\text{"ind"},m,son}) \\
&+\sum\nolimits_{r,rp,c,m}(\int smundem_{r,rp,c,\text{"mun"},m,son}\left(SURFACEDIVERSION_{r,rp,c,\text{"mun"},m,son}\right)dSURFACEDIVERSION_{r,rp,c,\text{"mun"},m,son} + \\
&\qquad\qquad \int sinddem_{r,rp,c,\text{"ind"},m,son}(SURFACEDIVERSION_{r,rp,c,\text{"ind"},m,son})dSURFACEDIVERSION_{r,rp,c,\text{"ind"},m,son}) \\
&-\sum\nolimits_{a,l,c,s,m} groudmunindpumpcost_{a,l,c,s,son} * (PUMPGROUND_{a,l,c,\text{"mun"},m,son} + PUMPGROUND_{a,l,c,\text{"ind"},m,son}) \\
&-\sum\nolimits_{r,rp,c,s,m} surfacemunindpumpcost_{c,s,m} * (SURFACEDIVERSION_{r,rp,c,\text{"mun"},m,son} + SURFACEDIVERSION_{r,rp,c,\text{"ind"},m,son}) \\
&-\sum\nolimits_{c,s,m} othergroudmunindpumpcost_{c,s,m,son} * (OTHERAQUIFER_{c,\text{"mun"},m,son} + OTHERAQUIFER_{c,\text{"ind"},m,son})
\end{aligned}\right\} \textbf{M\&I}
$$

$$
\left.\begin{aligned}
&+\sum\nolimits_{c,m} minprice_{c,m} * ADDUPUSERALL_{c,\text{"min"},m,son} \\
&-\sum\nolimits_{a,l,c,m} groundminpumpcost_{a,l,c,\text{"min"},son} * PUMPGROUND_{a,l,c,\text{"min"},m,son} \\
&-\sum\nolimits_{r,rp,c,m} surfaceminpumpcost_{c,m} * SURFACEDIVERSION_{r,rp,c,\text{"min"},m,son} \\
&-\sum\nolimits_{c,m} othergroundminpumpcost_{c,m} * OTHERAQUIFER_{c,\text{"min"},m,son}
\end{aligned}\right\} \textbf{Mining}
$$

$$
\left.\begin{aligned}
&+\sum\nolimits_{c,cr,ir}(cropprofit_{c,cr,ir,son} * CROPACRE_{c,z,cr,ir}) \\
&+\sum\nolimits_{c,ls,f}\left(liveprofit_{c,ls,f,son} * LIVEPROD_{c,ls,f}\right) \\
&-\sum\nolimits_{r,rp,c,m}(surfaceagpumpcost_{c,m} * SURFACEDIVERSION_{r,rp,c,\text{"ag"},m,son})
\end{aligned}\right\} \textbf{Ag}
$$

$$
\left.\begin{aligned}
&+\sum\nolimits_{r,rp,c,m}(recprice * SURFACEDIVERSION_{r,rp,c,\text{"rec"},m,son}) \\
&+\sum\nolimits_{r,rp,c,m}(otherprice - othercost) * SURFACEDIVERSION_{r,rp,c,\text{"oth"},m,son}
\end{aligned}\right\} \textbf{Recreation and Other}
$$

$$
\left.\begin{aligned}
&+\sum\nolimits_{wp}(annaulfixcost_{wp} * DO\_I\_OPRT\_WATER_{wp,son}) \\
&-\sum\nolimits_{wp,c,s,m}(variablecost_{wp} * PROJECTWATER_{wp,c,s,m,son})
\end{aligned}\right\} \textbf{TWDB Water Project}
$$

$$+\sum_{r,rp,m}(outtobayvalue * OUTTOBAY_{r,rp,m,son}) \qquad \textbf{Out to bay}$$

$$\left.\begin{aligned}
&+\sum_{pp,bt,ct,m} \int electricdem_{pp,bt,ct,m,son}\left(POWERPLANT\_GENERATION_{pp,bt,ct,m,son}\right)\; dPOWERPLANT\_GENERATION_{pp,bt,ct,m,son}\\
&-\sum_{pp,bt,ct} fixedom_{pp,bt,ct} * \left(DO\_I\_OPER\_POWERPLANT_{pp,bt,ct,son} + DO\_I\_OPER\_NEWNGPP_{pp,bt,ct,son}\right)\\
&-\sum_{pp,c,ws}(fixedom_{pp,c,ws} * WINDSOLAR\_OPERATION_{pp,ws,son})\\
&-\sum_{a,l,c,m}(groundcoolingpumpcost_{a,l,c,\text{"cooling"},son} * PUMPGROUND_{a,l,c,\text{"cooling"},m,son})\\
&-\sum_{r,rp,c,m}(surfacecoolingpumpcost_{c,m} * SURFACEDIVERSION_{r,rp,c,\text{"cooling"},m,son})\\
&-\sum_{fu,m}(fuelprice_{fu} * FUELCON_{fu,m,son}) + \sum_{fu,m}(fueltrans_{fu} * FUEL_{CON_{fu,m,son}})\\
&-\sum_{pp,bt,m}(penaltyweights * POWERPLANT\_GENERATION_{pp,bt,\text{"oncethrough"},m,son})\}
\end{aligned}\right\} \textbf{Power Plant}$$

$$\left.\begin{aligned}
&-\sum_{b}(annualcapcost_{b} * DO\_I\_BUILD\_WATER_{b})\\
&-\sum_{pz}(sprinklercost * LANDTRANSFER_{pz\text{"fur""sprk"}})\\
&-\sum_{pp,bt,ct,ct'}(coolingcapcost_{pp,ct,ct'} * DO\_I\_RETROFIT\_COOLING_{pp,bt,ct,ct'})\\
&-\sum_{pp,bt,bt',ct}(boilercapcost_{pp,bt,bt'} * DO\_I\_RETROFIT\_BOILER_{pp,bt,bt',ct})\\
&-\sum_{pp,bt,ct}(ngppcapcost_{pp,bt,ct} * DO\_I\_BUILD\_NEW\_NGPP_{pp,bt,ct})\\
&-\sum_{pp,c,ws}(windsolarcapcost_{pp,c,ws} * WINDSOLAR\_NEW_{pp,ws})
\end{aligned}\right\} \textbf{SON Independent Cost}$$

Constraints on land, crop, livestock, aquifer, surface water and electric generation are present below.

Crop mix constraint

Following (McCarl 1982), the crop mix constraint requires that crop harvested acres $(CROPACRE)$are a convex combination of historical crop mixes for dryland, irrigated and vegetable cases. This approach causes the model to generate realistic results without detailed resource modeling at the farm level (McCarl 1982). The crop mix constraint is represented as:

(4.1) $\sum_z CROPACRE_{c,z,cp,ir} = \sum_y cropmixdata_{c,cp,ir,y} CROPMIX_{c,ir,y} \qquad \forall\, z \; and \;\; y$

where $cropmixdata$ represents crop mix data by county (c), crop (cr), irrigation status $(dryland\ or\ irrigated\ land)$ which is a subset of land type (ir), and year (y); $CROPMIX$ is the crop mix variable, which is interpreted as the contribution factor from historical harvests.

Livestock mix constraint

Livestock production $(LIVEPROD)$ is set to be a convex combination of historical observable livestock species by county, where f denotes feeding methods (pasture land or grazing land). Livestock mix is defined in equation (4.2):

(4.2) $\sum_f livebudget_{c,ls,f} LIVEPROD_{c,ls,f} = \sum_y livemixdata_{c,ls,y} LIVEMIX_{c,y} \;\; \forall\, c \; and \; ls$

where $livebudget$ is the head of livestock defined on per animal unit basis, $livemixdata$ represents livestock mix data by county (c), livestock (ls), and year (y), $LIVEMIX$ is the livestock mix variable, which is interpreted as the contribution factor from historical livestock inventory.

Land availability constraint

Equations (4.3) and (4.4) limits land availability covering irrigated land, dryland and pasture land for agriculture. Land types (ir) are furrow land, sprinkler land, dryland, and pasture land. In the notation we use ir' to indicate the type of land after conversion, or land transferred from other types.

- When the land type is furrow irrigated land, crop production is limited to furrow land available ($AvailableLand$) in a county and zone, with the model allowing furrow land acres to be converted ($LANDTRANS$) to sprinkler land, dryland, and pasture land.
- For sprinkler land, crop production cannot exceed initial sprinkler land available plus that transferred from furrow land in a county and zone, and also allows sprinkler land to convert to dryland or pasture land.
- For dryland, the crop acres on the dryland is limited to available dryland plus the land transferred from furrow and sprinkler irrigated land, we also consider land conversion between dryland and pasture land.
- Pasture land in a county is limited to available pasture land plus that transferred from irrigated land or dryland.
- When new wind or solar power plants (pp) are built, $WINDSOLAR\_LAND$ is the variable representing land acres for installation wind or solar plants (ws) in county (c) , zone (z).

$$\text{(4.3)} \quad \sum_{cr} CROPACRES_{c,z,cr,ir} + \sum_{ir'} LANDTRANS_{c,z,ir,ir'} + \sum_{pp,ws} WINDSOLAR\_LAND_{pp,ws,c,z,ir} \leq AvailableLand_{c,z,ir} + \sum_{ir'} LANDTRANS_{c,z,ir',ir} \qquad \forall c, z, and\ ir$$

(4.4) $PASTURE_c + \sum_{pp,ws,z} WINDSOLAR\_LAND_{pp,ws,c,z,"pasture"} \leq$

$\sum_z AvailableLand_{c,z,"pasture"} + \sum_{z,ir'} LANDTRANS_{c,z,ir',"pasture"} \quad \forall c$

Crop irrigation water usage balance

The irrigated crop water demand from per acre rates times the acres of each crop strategy use is equated to a variable giving total water needed for irrigation ($AGZONEWATERUSE$) by county (c), zone (z), month (m), water source (ra) which is a upper set of all rivers and aquifers, and state of nature (son). See equation (4.5) below:

(4.5) $\sum_{cr,ir,cs} stratdata_{c,cr,ir,son,cs,"water"} CROPSTRATEGY_{c,z,cr,ir,son,cs} =$

$\sum_{ra} AGZONEWATERUSE_{c,z,m,ra,son} \quad \forall\ c, z, m\ and\ son$

where $stratdata$ is the monthly crop water use under alternative irrigation strategies (cs), $CROPSTRATEGY$ is the crop strategy variable for crop harvest acres.

Irrigated water supply demand balance

This constrain balances irrigated water total demand with supply from multiple sources, limiting irrigated water use to the total amount of agricultural supply arising from: major groundwater aquifers ($PUMPGROUND$), surface water($SURFACEDIVERSION$), other minor aquifers ($OTHERAQUIFER$), and water from TWDB projects ($AGPROJECTSUPPLY$).

(4.6) $\sum_z AGZONEWATERUSE_{c,z,m,ra,son} = \sum_l PUMPGROUND_{a,l,c,"ag",m,son} +$

$\sum_{rp} SURFACEDIVERSION_{r,rp,c,"ag",m,son} + OTHERAQUIFER_{c,"ag",m,son} +$

$AGPROJECTSUPPLY_{c,ra,m,son} \quad \forall\ c, m, ra, and\ son$

River system balance

The river system node balance (equation 4.7) portrays a hydrological balance at nodes along a river. This balances inflows with outflows. Inflows arise from upstream, springflow, return flows, reservoir withdrawals, water from surface projects and net new additions. Outflows include flows to downstream, reservoir additions, user diversions, aquifer injections, and flows to bays.

$$
\begin{aligned}
\text{(4.7)}\quad & \textstyle\sum_{c,s} SURFACEDIVERSION_{r,rp,c,s,m,son} + \sum_{rp'} FLOWout_{r,rp,rp',m,son} + \\
& TOBAY_{r,rp,m,son} + STOREadd_{rs,m,son} + \textstyle\sum_{wp,c,a} QINJECTS_{wp,r,rp,c,a,m,son} + \\
& \textstyle\sum_{wp,c,s} USESURFACEPROJECT_{wp,r,rp,c,s,m,son} + \sum_{wp,ocr,c} QINJECTOCR_{wp,r,rp,ocr,c,m,son} \\
= {} & inflow_{r,rp,m,son} + \textstyle\sum_{rp'} FLOWin_{r,rp',rp,m,son} + STOREwithdraw_{rs,m,son} + \\
& SPRINGDIS_{sp,son} + \textstyle\sum_{s} RFrate_{s} * \sum_{a,l,c,s} PUMPGROUND_{a,l,c,s,m,son} + \sum_{s} RFrate_{s} * \\
& \textstyle\sum_{c,s} SURFACEDIVERSION_{r,rp,c,s,m,son} + \sum_{s} RFrate_{s} * \\
& \textstyle\sum_{wp,c,s} USESURFACEPROJECT_{wp,r,rp,c,s,m,son} + RFrate * \\
& \textstyle\sum_{pp,bt,ct} waterusage_{pp,bt,ct,m,son} * POWERPLANT\_GENERATION_{pp,bt,ct,m,son} \\
& \hfill \forall\, r, rp, m, and\ son
\end{aligned}
$$

where $inflow$ is the net water increase to the river system from new inflows directly into the river (r), river place (rp) in month (m), under state of nature (son) ; $FLOWout$ is the water flows out from a river place (rp) to downstream (rp'), and $FLOWin$ is the water flows in from upstream river places (rp'); $TOBAY$ represents water flow to the bay and estuary; $STOREadd$ and $STOREwithdraw$ denote water releases from and retention in the reservoir (rs) in current month (m); $QINJECTS$ is the injection of water to aquifer (a) in county (c) from surface water under a water project (wp); $QINJECTOCR$ is surface water diverted to off-channel reservoir (ocr) in county (c) under water project (wp); $USESURFACEPROJECT$ is water from a surface water project (wp); $SPRINGDIS$ represents spring (sp) discharges to river; $RFrate$ is the water return flow proportion from usage by water use sector (s). When power plants using once-through cooling systems are operating, we assume 90 percent of cooling water use for power generation ($POWERPLANT\_GENERATION$) will return to the diversion point.

Aquifer elevation determination

The ending level of an aquifer is determined by incorporating a response function giving ending elevation as a function of aquifer recharge, initial water level, and groundwater pumping following Keplinger and McCarl (1995). The regression parameters were estimated via OLS regressions over groundwater simulation models. The ending lift of the aquifer is a function of pumping use, and the unit cost of pumping is a function of the end lift, thus the total cost of pumping in the objective function equals the unit cost of pumping times pump use, which yields a nonlinear term. We use a stepwise variable to represent various amounts of pumping used ($pump\_step$), by doing this we linearize the pumping cost term in the model.

Springflow amounts

Springflows ($SPRINGFLOW$) are also modeled and are specified by including a regression again following Keplinger and McCarl (1995). That regression projects springflow as a function of the initial Edwards Aquifer elevation level at the J17 reference well ($initiallevel$), the ending level elevation at the J17 well ($ENDLEVEL$), the Edwards Aquifer recharge ($Recharge$), and the Edwards Aquifer pumping level at county level ($TOTALCOUNTYPUMP$).

$$(4.8)\quad SPRINGFLOW_{sp,son} = rsprnint_{sp} + rsprnr_{sp} * Recharge_{son} + rsprnu_{sp} * \sum_{c,m} TOTALCOUNTYPUMP_{c,"edwards",m,son} + rsprni_{sp} * initiallevel + rsprne_{sp} * ENDLEVEL_{son} \qquad \forall\ sp\ and\ son$$

where $rsprnint$ is the estimated intercept, $rsprnr$ is the parameter of recharge, $rsprnu$ is the parameter of Edwards Aquifer pumping use, $rsprni$ is the initial water level parameter, $rsprne$ is the ending water level parameter.

Power plant electricity generation

Monthly electricity generation ($POWERPLANT\_GENERATION$) is limited by capacity, by type of boiler (bt), type of cooling system (ct) of exist power plants (pp') and new NGCC plants (pp''). The available generation is the designed capacity times a capacity factor times the number of hours operation of each plant.

(4.9)
$$POWERPLANT\_GENERATION_{pp,bt,ct,m,son} \leq capacity_{pp,bt,ct} * capacityfactor_{pp,bt,ct} * time * [DO\_I\_OPER\_POWERPLANT_{pp\in pp',bt,ct,son} + DO\_I\_OPER\_NEW\_NGPP_{pp\in pp'',bt,ct,son}] \qquad \forall pp \in pp' \cup pp'',\ bt, ct, m, and\ son$$

where $DO\_I\_OPER\_POWERPLANT$ is a binary variable to indicate whether to operate exist power plant; $DO\_I\_OPER\_NEW\_NGPP$ is the binary variable to indicate whether to operate new NGCC plant.

Power plant retrofit limits

Equation (4.10) controls the retrofit possibility. The variable $DO\_I\_RETROFIT\_COOLING$ is a binary variable indicating whether to retrofit cooling systems of power plant. If the model choose not retrofit cooling system to an advanced one (ct'), $DO\_I\_RETROFIT\_COOLING$ equals 0, then the model could choose whether or not to operate the power plant with existing cooling system (ct); if the model choose retrofit cooling system to an advanced one (ct'), $DO\_I\_RETROFIT\_COOLING$ equals 1, then we could not operate power plant with existing cooling system (ct) any more, and equation (4.11) will be the constraint after retrofitting, the model could choose whether or not to operate power plant with retrofitted cooling system (ct'). We also have the same constraint for retrofitting boiler ($DO\_I\_RETROFIT\_BOILER$). Note retrofits of either the boiler or cooling system are only allowed to occur once (equation 4.12).

(4.10) $DO\_I\_OPER\_POWERPLANT_{pp,bt,ct,son} +$

$\sum_{ct'} DO\_I\_RETROFIT\_COOLING_{pp,bt,ct,ct'} \leq 1 \qquad \forall\, pp, bt, ct, son$

(4.11) $DO\_I\_OPER\_POWERPLANT_{pp,bt,ct',son} -$

$\sum_{ct} DO\_I\_RETROFIT\_COOLING_{pp,bt,ct,ct'} \leq 0 \qquad \forall\, pp, bt, ct', son$

(4.12) $\sum_{bt,ct,ct'} DO\_I\_RETROFIT\_COOLING_{pp,bt,ct,ct'} +$

$\sum_{bt,bt',ct} DO\_I\_RETROFIT\_BOILER_{pp,bt,bt',ct} \leq 1 \qquad \forall pp$

Wind solar operation

Equation (4.13) is the wind and solar plant operation capacity constraint which limits the total number of new renewable plants in operation ($WINDSOLAR\_OPERATION$) to the existing number of new renewable plants built in previous period ($windsolar\_newexist$) plus the number of new renewable plants being built in current period ($WINDSOLAR\_NEW$). Equation (4.14) is the wind and solar plant generation constraint which limits the total generation ($WINDSOLAR\_GENERATION$) from new wind or solar plants to the number of new wind or solar plants in operation ($WINDSOLAR\_OPERATION$) times generation in MWh ($windsolar\_generation$) per 1000 square meters solar panel or per wind turbine.

(4.13) $WINDSOLAR\_OPERATION_{pp,ws,son} \leq WINDSOLAR\_NEW_{pp,ws} +$

$windsolar\_newexist_{pp,ws} \qquad \forall pp, ws, son$

$$\text{(4.14)}\quad WINDSOLAR\_GENERATION_{pp,ws,son} \leq windsolar\_generation_{pp,ws,son} * WINDSOLAR\_OPERATION_{pp,ws,son} \qquad \forall pp, ws, son$$

Power plant capacity requirement

The peak generation is in August, thus plant capacity in August is greater than or equal to electricity demand in the region ($ELEC\_DEMAND\_COUNTY$) adjusted by peak factor. pp represents existing power plant and new NGCC plant, whereas pp' represents new wind and solar plant.

$$\text{(4.15)}\quad \left[\sum_{pp,bt,ct} POWERPLANT_{GENERATION_{pp,bt,ct,\text{"Aug"},son}} + \sum_{pp',ws} WINDSOLAR\_GENERATION_{pp',ws,son}\right] / Hours \geq peakfactor * \sum_{c} ELEC\_DEMAND\_COUNTY_{c,\text{"}Aug\text{"},son} \qquad \forall son$$

where $POWERPLANT\_GENERATION$ is the power generation from existing plants or new NGCC plants; $WINDSOLAR\_GENERATION$ is the power generation from new wind or solar plants. Wind and solar capacity from existing plants (pp') plus the new plants (pp''') are also constrained to 25% of the total power plant capacity in the region, see equation (4.16) below:

$$\text{(4.16)}\quad \sum_{pp,bt,ct} capacity_{pp,bt,ct} * \left[DO\_I\_OPER\_POWERPLANT_{pp\in pp'',\text{"}solar\text{"},ct,son} + DO\_I\_OPER\_POWERPLANT_{pp\in pp'',\text{"}wind\text{"},ct,son}\right] + \sum_{pp''',ws} windsolarcapacity_{pp''',ws,son} * WINDSOLAR_{OPERATION_{pp''',ws,son}} \leq 0.25 * \{\sum_{pp,bt,ct} capacity_{pp,bt,ct} * [DO\_I\_OPER\_POWERPLANT_{pp\in pp',bt,ct,son} + DO\_I\_OPER\_NEW\_NGPP_{pp\in pp'',bt,ct,son}] + \sum_{pp''',ws} windsolarcapacity_{pp''',ws,son} * WINDSOLAR\_OPERATION_{pp''',ws,son}\} \qquad \forall\ son$$

Electricity supply demand balance

Electricity per capita demand ($ELEC\_PERCAP$) times total population in the region is greater than or equal to the regional electricity demand in each month.

(4.17) $totalpop * ELEC\_PERCAP_{m,son} \geq elecdemand_m \qquad \forall m\ and\ son$

Equation (4.18) explains electricity supply demand relationship. We use population in each county (c) times electricity per capita demand ($ELEC\_PERCAP$) to denote municipal and industrial electricity demand in each county; energy demand in that county also raises from implementing TWDB water projects ($OTHERELECDEMAND$). These electricity demands are limited to electricity demand in each county ($ELEC\_DEMAND\_COUNTY$) plus the electricity gap, we use the current gap to denote electricity import from other regions.

(4.18) $popoulation_c * ELEC_{PERCAP_{m,son}} + OTHERELECDEMAND_{c,m,son} \leq$

$ELEC\_DEMAND\_COUNTY_{c,m,son} + \ electricgap_{c,m} \qquad \forall c, m, and\ son$

Electricity demand from water projects ($OTHERELECDEMAND$) equals pumping energy used per acre-foot of water yield ($unit\_pumping\_energy$) times water yield from groundwater projects ($USEGROUNDPROJECT$), ASR projects ($RECOVER$), surface water projects($USESURFACEPROJECT$), off-channel-reservoir projects ($RECOVER\_OCR$), and projects using out of region water sources($USEOUTSIDEPROJECT$). See equation (4.20) below:

(4.19) $OTHERELECDEMAND_{c,m,son} = \sum_{wp,s,c',a,l} unitpumpingenergy_{wp} *$

$USEGROUNDPROJECT_{wp,c,s,c',a,l,m,son} +$

$\sum_{wp,s,c',a} unitpumpingenergy_{wp} * RECOVER_{wp,c,s,c',a,m,son} +$

$\sum_{wp,r,rp,s} unitpumpingenergy_{wp} * USESURFACEPROJECT_{wp,r,rp,c,s,m,son} +$

$\sum_{wp,s,\mathrm{ocr},c'} unitpumpingenergy_{wp} * RECOEROCR_{wp,c,s,\mathrm{ocr},c',m,son} +$

$\sum_{wp,s} unitpumpingenergy_{wp} * USEOUTSIDEPROJECT_{wp,c,s,m,son} \qquad \forall c, m, and\ son$

The electricity demand in each county (c) is limited to the electricity generated from where power plants located (c') after considering the transmission loss percentage ($elecloss$) (equation 4.20). Electricity transmission ($ELEC\_TRANS$) from the source county (c') to the destination county (c) is limited to plant generation in the source county (equation 4.21). pp' represents existing plant or new NGCC plant, whereas pp'' represents new wind or solar plant.

(4.20) $ELEC\_DEMAND\_COUNTY_{c,m,son} \le \sum_{c'}[(1 - elecloss_{c',c}) * ELEC\_TRANS_{c',c,m,son}]$

$\forall c, m, and\ son$

(4.21) $\sum_{c'} ELEC\_TRANS_{c',c,m,son} \le \sum_{pp',bt,ct} POWERPLANT\_GENERATION_{pp',bt,ct,m,son} +$

$\sum_{pp'',ws} WINDSOLAR\_GENERATION_{pp'',ws,son} \qquad \forall c, m, and\ son$

Power plant fuel usage

Fuel usage by power generation is limited to the fuel consumption ($FUEL\_CONS$) by type (fu) in the region. The total heat from generation is equal to plant generation times heat rate ($heatrate$) in MMBtu per MWh, and then the total fuel use is equal to the total heat divided by the heat rate contained in per unit of fuel ($fuelheat$).

(4.22) $\sum_{pp,bt,ct}(heatrate_{pp,bt,ct} * POWERPLANT\_GENERATION_{pp,bt,ct,m,son}/$

$fuelheat_{pp,bt,fu}) \le FUEL\_CONS_{fu,m,son} \qquad \forall fu, m, and\ son$

Power plant water use

The following two equations display power plant cooling water use from surface water and groundwater, $waterusage$ is the consumptive cooling water use in acre-foot per MWh.

$$(4.23)\ \sum_{pp,bt,ct} waterusage_{pp,bt,ct,m,son} * POWERPLANT\_GENERATION_{pp,bt,ct,m,son} = SURFACEDIVERSION_{r,rp,c,\text{"cool "},m,son} \qquad \forall r, rp, c, m, and\ son$$

$$(4.24)\ \sum_{pp,bt,ct} waterusage_{pp,bt,ct,m,son} * POWERPLANT\_GENERATION_{pp,bt,ct,m,son} = PUMP\_GROUND_{a,l,c,\text{"cool"},m,son} \qquad \forall a, l, c, m, and\ son$$

Renewable plant land use

Equation (4.25) is the land use balance for new renewable power plants. Land use of wind or solar farm ($WINDSOLAR\_LAND$) is set to be greater than or equal to land use of per unit of panel or turbine ($landuse$) times the number of panels or turbines are being used ($WINDSOLAR\_NEW$).

$$(4.25)\ \sum_{z,ir} WINDSOLAR\_LAND_{pp,ws,c,z,ir} \geq landuse_{pp,c,ws} * WINDSOLAR\_NEW_{pp,ws} \qquad \forall pp, c, ws$$

Equation (4.26) is the land use availability for renewable power plants. Land use by county (c), zone (z), and land type (ir) summed across new and exist renewable power plant is restricted to 10% of available land type (ir) after considering land transfers.

$$(4.26)\ \sum_{pp,ws} WINDSOLAR\_LAND_{pp,ws,c,z,ir} + \sum_{pp,ws} windsolarlandexist_{pp,ws,c,z,ir} \leq 0.1 * \left[AvailableLand_{c,z,ir} - LANDTRANS_{c,z,ir,ir'} + LANDTRANS_{c,z,ir',ir}\right] \qquad \forall c, z, and\ ir$$

Hydroelectric plant generation

The following equation is the power generation from hydroelectric plant.

$$(4.27)\ POWERPLANT\_GENERATION_{pp,\text{"}hydro\text{"},\text{"}none\text{"},m,son} \leq head_{pp} * \sum_{r,rp,rp'} FLOW_{r,rp,rp',m,son} * gravity * efficiency * Hours_m \qquad \forall pp, m, and\ son$$

where $head$ is the difference in elevation between water surface in the reservoir and in the tailrace; $FLOW$ is the volume of water to turn the turbine generator; $gravity$ is the acceleration due to gravity, which is approximately 9.81 m/s^2; we assume the efficiency of the generator is 60 percent.

4.6. Model Scenario Design

Scenarios were set up to explore the effects of population growth and climate change on electricity sector in the content of full FEW Nexus.

- We use the climate condition and population in 2015 as baseline model. We will specify electricity supply and demand in the content of full FEW Nexus. In particularly, we will examine electricity demand, wholesale price, power plant capacity, cooling water use, cooling and boiler retrofit, and welfare in electricity sector in the baseline model.
- An increased demand for FEW components as a result of rapid population growth rate will be examined. In those scenarios, regional population increase 50 percent by 2050 relative to the base model for the year 2015, and this number further doubles by 2090(You et al. 2019). We will specify how electricity demand changes compared to base model when population increases. Subsequently, cooling water use, cooling retrofits, and new power capacity added are analyzed to address how it changes to meet an increasing demand in electricity.
- Changes in climatic conditions in the region will further alter FEW components demand and supply. An increase in temperature will cause an increase in water demand for agricultural production, municipal use, and power generation, but also will increase evaporation, lowering runoff and in turn aquifer recharge. A decrease in rainfall will

increase agricultural, municipal, and power plant water demand, and reduce the available water for recharge. The GCMs under different RCP describe future climate condition in terms of climate change driving forces including population growth. We will examine power plant generation and cooling water use, new capacity added to the region, and cooling and boiler retrofits in the content of full FEW Nexus in future climate condition.

The specified scenarios are in Table 4.3. We use the wettest and driest GCMs as specified before.

Table 4.3 Definition of scenarios in EDSIMRGW_NEX

Scenarios	Definition
2015baseline	no population growth and no climate change
no climate effect	no climate change from 2030 to 2090
MIROC5 RCP2.6	the wettest climate scenario under RCP 2.6 from 2030 to 2090
MIROC5 RCP4.5	the wettest climate scenario under RCP 4.5 from 2030 to 2090
MIROC5 RCP6.0	the wettest climate scenario under RCP 6.0 from 2030 to 2090
MIROC5 RCP8.5	the wettest climate scenario under RCP 8.5 from 2030 to 2090
IPSL-CM5A-LR RCP2.6	the driest climate scenario under RCP2.6 from 2030 to 2090
IPSL-CM5A-LR RCP4.5	the driest climate scenario under RCP4.5 from 2030 to 2090
IPSL-CM5A-LR RCP6.0	the driest climate scenario under RCP6.0 from 2030 to 2090
IPSL-CM5A-LR RCP8.5	the driest climate scenario under RCP8.5 from 2030 to 2090

4.7. Model Results and Discussion

In this section, we first solve the base model for the year 2015, assuming no climate change and no population growth in this scenario. Then we solve the model with and without climate change from year 2030 to year 2090, and report the results on welfare, electricity price index, electricity demand quantity, cooling water usage, power plant capacity, new plant potential, cooling and boiler retrofits.

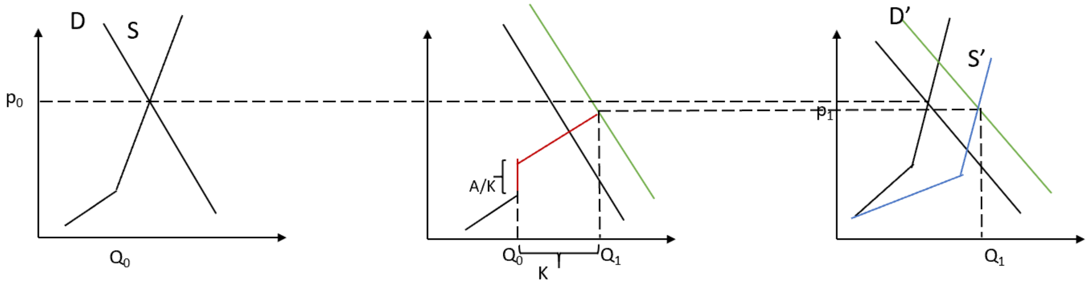
4.7.1. Energy Price Index

In Table 4.4, we see that electricity Fisher price index generally decreases until before 2050 in all scenarios compared to the index in 2015, and increases beyond 2050 in some scenarios. When the increase in power plant supply capacity (see 4.7.4. new capacity added) exceed the increase in electricity demand before 2050, resulting in the shift of supply curve more than the shift of demand curve, Fisher price index decreases. On the other hand, when new plant capacity increases little after 2050 or power plants retrofit cooling systems to dry cooling systems, which reduce supply capacity, Fisher price index increases.

Table 4.4 Comparison of climate effect and population growth impact on Fisher price index

Scenario	2030	2050	2070	2090
	percentage change from baseline			
no climate change	-3.73	-0.88	4.58	6.75
IPSL-CM5A-LR RCP2.6	-9.44	-5.56	-0.77	-1.77
IPSL-CM5A-LR RCP4.5	-8.82	-0.98	-2.43	3.65
IPSL-CM5A-LR RCP6.0	-10.87	-14.11	-14.23	-2.32
IPSL-CM5A-LR RCP8.5	-10.02	-11.28	-3.23	9.34
MIROC5 RCP2.6	-6.69	-2.74	-2.13	-0.45
MIROC5 RCP4.5	-4.81	-3.45	1.30	1.89
MIROC5 RCP6.0	-8.51	-3.27	0.04	8.20
MIROC5 RCP8.5	-10.35	0.18	-4.31	7.74

We can understand the Fisher price index changes by looking at the shift of demand and supply curves in Figure 4.1. Suppose electricity demand in year 2015 is D and supply curve from current operating power plant is S in panel (a). Note supply curve reaches inelastic portion when the region needs to import electricity from other regions. Now suppose we include the possibility of building new plants in the year 2030, meanwhile electricity demand curve is shifting outward because of population growth and temperature rise, we assume demand curve is of the constant elasticity form. We also assume that new plants will add volume K capacity and the amortized fixed cost is A (Wang, Wlodarz and McCarl 2019). Then the supply curve would jump up in price by A/K, and proceed out to deliver more supply at the marginal cost curve but with A/K added at all capacity volumes as in panel (b). Once new capacity is added in subsequence years, plant will operate at the new supply curve S', and the new electricity demand curve will be D' as in panel (c).



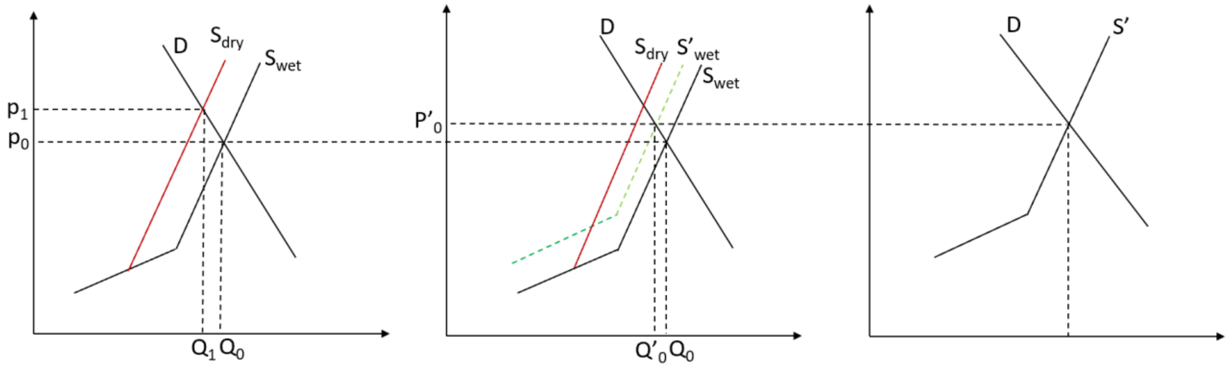
Panel (a) existing plant

Panel (b) add new capacity and demand

Panel (c) new demand and supply

Figure 4.1. Demand and supply curves of power plant expansion

In Figure 4.2, we see more information on electricity demand and supply when considering cooling retrofits. We assume demand is unchanged under state of nature, the black solid lines in panel (a) depict the demand supply relationship under wet condition. When less cooling water is available under a dry state, power plants downscale operations, and electricity prices increase, we use red line to denote supply curve under dry state in panel (a). Given this basic setup, consider panel (b) where we retrofit cooling systems of power plants. Power plants are now operating at the green dashed line under wet condition because of increased fixed cost, then, in this case, by retrofitting cooling systems electricity price and generation are less sensitive to state of nature. Panel (c) shows plants in dry and wet state operate at the same supply curve after retrofitting cooling systems.



Panel (a) before cooling retrofit

Panel(b) cooling retrofit

Panel (c) after cooling retrofit

Figure 4.2. Power plant cooling retrofits under dry and wet states

4.7.2. Estimation Electricity Demand

Changes in electricity price are caused in part by increased electricity demand, electricity demand in the ERCOT region exhibits a large peak in the summer months, with a moderate winter peak(Searcy 2011). Since population growth and climate conditions would induce a response in electricity demand, a regression-based method below provides insight to estimate electricity demand in future decades.

We specify and then estimate a regression model (equation 4.29) that relates electricity demand in the context to temperature variations and population growth. Table 4.5 represents a summary of regression results from OLS estimation. The sign for $log(population)$ is positive, indicating long term upward trend in electricity demand. $SummerTerm$ captures the primary peaks due to high air conditioning loads, and $WinterTerm$ captures the secondary peaks due to heat loads. Equation (4.30) specifies the assumption for $SummerTerm$ and $WinterTerm$.

(4.28) $$log(electricitydemand) = \beta_0 + \beta_1\, log(population) + \beta_2 SummerTerm + \beta_3 WinterTerm + \mu$$

(4.29) $$SummerTerm = \begin{cases} Temp - 20.5\ degC & for\ Temp > 20.5\ degC \\ 0 & for\ Temp \leq 20.5\ degC \end{cases}$$

$$WinterTerm = \begin{cases} Temp - 15.5\ degC & for\ Temp < 15.5\ degC \\ 0 & for\ Temp \geq 15.5\ degC \end{cases}$$

Monthly temperature (°C) in Bexar County from year 2002 to 2016 are obtained from PRSIM Climate Data(PRISM 2018). Population by counties in the region are obtained from the U.S Census Bureau(United States Census Bureau 2018). Historical electricity demand is from ERCOT hourly load data(ERCOT 2018), the loads are divided by ERCOT weather zone, South Central Texas falls in South and South Central weather zone, then we convert hourly data to monthly average load data in MW.

Table 4.5 OLS regression for electricity demand

	Coef.	Std	P>|z|
Constant	-4.973	0.428	0.000
log(population)	0.887	0.027	0.000
$SummerTerm$	0.046	0.001	0.000
$WinterTerm$	-0.014	0.002	0.000
Obs	180		
Adjusted R-squared	0.964		

We use the above estimated coefficients to predict regional electricity demand under population growth and climate change scenarios, and then divide by the electricity demand in 2015, which yields the quantity index in all scenarios (Table 4.6). In the no climate change scenario, we find electricity demand increases 15.27 percent by 2030, and this number further increases along with population growth in subsequence decades. Under climate change, electricity demand increases 135.84 percent, at most, in 2090, as shown in the IPSL-CM5A-LR

GCM results under RCP 8.5. Moreover, the forecasted climate change in IPSL-CM5A-LR model is shown to increase electricity demand greater than that in MIROC5 model, since temperatures predicted from IPSL-CM5A-LR are higher than those under MIROC5. Comparing electricity demand with and without climate change effect, we see that electricity demand significantly increases when temperature rise under climate change.

Table 4.6 Comparison of climate effect and population growth on electricity demand index

Scenario	2030	2050	2070	2090
	percentage change from baseline			
no climate change	15.27	36.81	60.81	88.81
IPSL-CM5A-LR RCP2.6	21.76	44.81	70.81	100.02
IPSL-CM5A-LR RCP4.5	23.40	47.52	76.04	108.12
IPSL-CM5A-LR RCP6.0	22.53	51.84	80.82	109.38
IPSL-CM5A-LR RCP8.5	22.62	54.92	90.12	135.84
MIROC5 RCP2.6	20.51	43.25	68.44	99.49
MIROC5 RCP4.5	22.07	44.98	73.74	104.17
MIROC5 RCP6.0	20.87	45.46	73.08	104.56
MIROC5 RCP8.5	21.94	47.97	83.16	119.88

4.7.3. TWDB Water Projects Electricity Demand

A set of optimal regional water projects were chosen by solving EDSIMRGW_NEX under water demand in the year 2015 and future decades, these water projects have high pumping energy requirements, making pumping energy use from water projects a large component in overall electricity demand. Figure 4.3 shows electricity demand from TWDB projects, with annual electricity demand and water yield from implementing these projects. The yield from water project is 49, 078 acre-feet, with pumping energy at 36 GWh in 2015. When water yield from projects increase, electricity demand also increases.

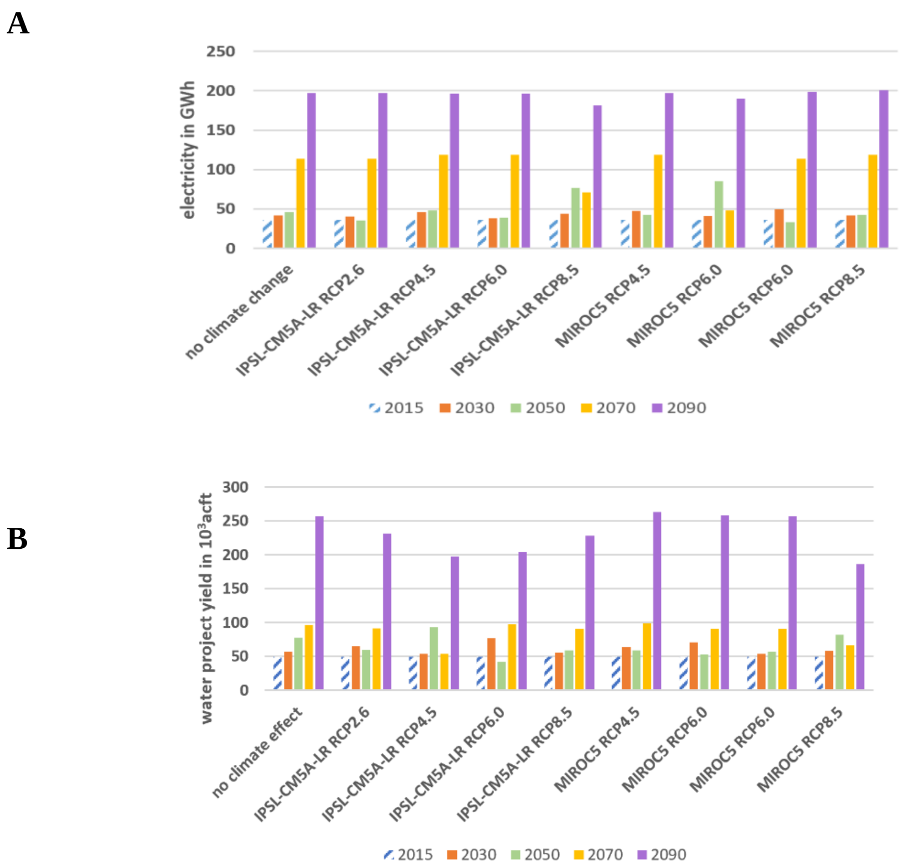


Figure 4.3 TWDB water projects. (A) Electricity demand from water projects. (B) Water yields from projects

4.7.4. Power Plant Capacity

Now let us address regional power plant capacity under different scenarios. The total regional capacity in future decades includes the capacity of all existing power plants, new NGCCs, and new renewable power plants. In Table 4.7, we find power plant capacity increases from 24.21 percent to 107.35 percent along with population growth from year 2030 to 2090 under no climate change scenario. In climate change scenarios, IPSL-CM5A-LR and MIROC5 under RCP2.6, RCP4.5, RCP6.0, and RCP8.5 report consistently increasing in plant capacity. There is a substantial increase in plant capacity, 129 percent, at most, in 2090 under MIROC5 RCP8.5. Furthermore, across the two climate models we see that plant capacity generally increases more in IPSL-CM5A-LR than that in MIROC5 under the same greenhouse emission scenario. This indicates that drier condition results in more capacity added to the region. However, the total capacity in MIROC5 is greater than that in IPSL-CM5A-LR under RCP 8.5 in 2070 and 2090, since new capacity from wind farms is greater in MIROC5 (see Figure 4.4).

Table 4.7 Comparison of climate scenarios effect on power plant capacity

Scenarios	2030	2050	2070	2090
	percentage change from base scenario			
no climate effect	24.21	47.02	66.18	107.35
IPSL-CM5A-LR RCP2.6	39.15	60.46	79.84	94.87
IPSL-CM5A-LR RCP4.5	39.71	61.02	81.54	95.68
IPSL-CM5A-LR RCP6.0	40.81	72.84	93.82	105.43
IPSL-CM5A-LR RCP8.5	40.80	72.84	96.44	118.78
MIROC5 RCP2.6	36.37	57.75	97.40	112.41
MIROC5 RCP4.5	38.97	60.37	81.38	92.17
MIROC5 RCP6.0	39.06	60.38	81.38	94.27
MIROC5 RCP8.5	39.04	83.38	107.01	129.00

When demand for electricity increase, new power plants are being built in subsequent years. Figure 4.4 displays the cumulative increased capacity of new NCGGs, solar plants and wind plants in the region. The added capacity of new plants is gradually increasing from 2030 to 2090 in each scenario. Figure 4.5 shows locations of new plants in the region by type. NGCCs are built near coastal, wind and solar are built in the central region. The number of new plants added in all scenarios are shown in Table 4.8, it describes the number of new NGCC plants, wind turbines and solar panels in the region. There are at most 3 new NGCCs being built in 2050 (in IPSL-CM5A-LR RCP 6.0 and IPSL-CM5A-LR RCP8.5), and these plants are built with recirculating cooling systems, the number of new NGCCs being built in the region is limited by available water permits. As new water permits are not issued for them, existing permits are not enough to assign to new NGCCs, in particularly when cooling water needs increase with higher temperature and less precipitation. Thus, we see the number of renewable plants increases a lot in order to meet electricity demand.

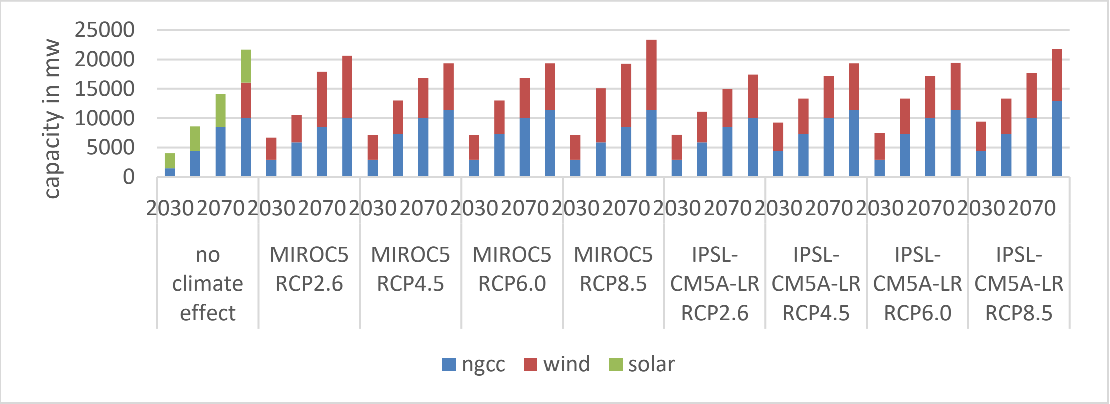


Figure 4.4 The cumulative new capacity added by type of plants

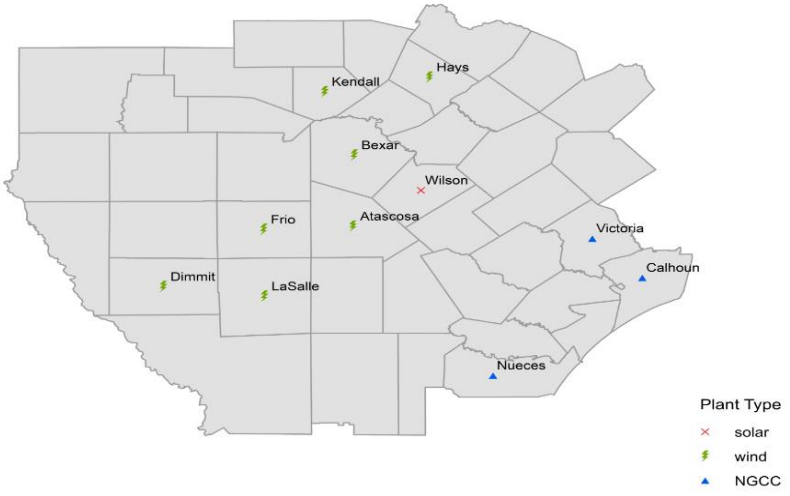


Figure 4.5 Locations of new plants being built in the region

Table 4.8 Number of new plants built in the region

	2015			2030			2050			2070			2090		
scenarios	NGCC	wind turbine	solar panel	NGCC	wind turbine	solar panel	NGCC	wind turbine	solar panel	NGCC	wind turbine	solar panel	NGCC	wind turbine	solar panel
no climate effect	2			1		20781	2		8743	2		6146	1	11849	
IPSL-CM5A-LR RCP2.6		5012		2	1154		2	1062		2			1	1519	
IPSL-CM5A-LR RCP4.5		5134		2	1154		2	1307		2			1	1340	
IPSL-CM5A-LR RCP6.0		5371		2	1735		3	1414		2			1	797	
IPSL-CM5A-LR RCP8.5		5370		2	1735		3	1980		2			2	1418	
MIROC5 RCP2.6		7274		2	1489		2	6934		2			1	1941	
MIROC5 RCP4.5		6322		2	1492		2	1800		2			1	778	
MIROC5 RCP6.0		6347		2	1471		2	1797		2			1	1358	
MIROC5 RCP8.5		6343		2	6143		2	1982		2			2	1339	

4.7.5. Water Use

Figure 4.6 shows the changes in cooling water use by power plants with and without climate change. When there is no climate change, cooling water use is gradually increasing along with an increasing demand in electricity, cooling water use was 577 acre-feet in 2015 and increases by 239 acre-feet in 2030 and further increases by 2,248 acre-feet in 2090. When climate change factors in, higher temperature further increases electricity demand, cooling water use increases by 479 acre-feet in 2030 in IPSL-CM5A-LR under RCP8.5, and this number further increases by 3,703 acre-feet in 2090. Comparing cooling water use in IPSL-CM5A-LR and MIROC5 under extreme greenhouse emission scenarios (RCP6.0 and RCP8.5), we find higher temperature and less precipitation (IPSL-CM5A-LR) result in more cooling water use in the same decade, as more power generation is required in drier condition.

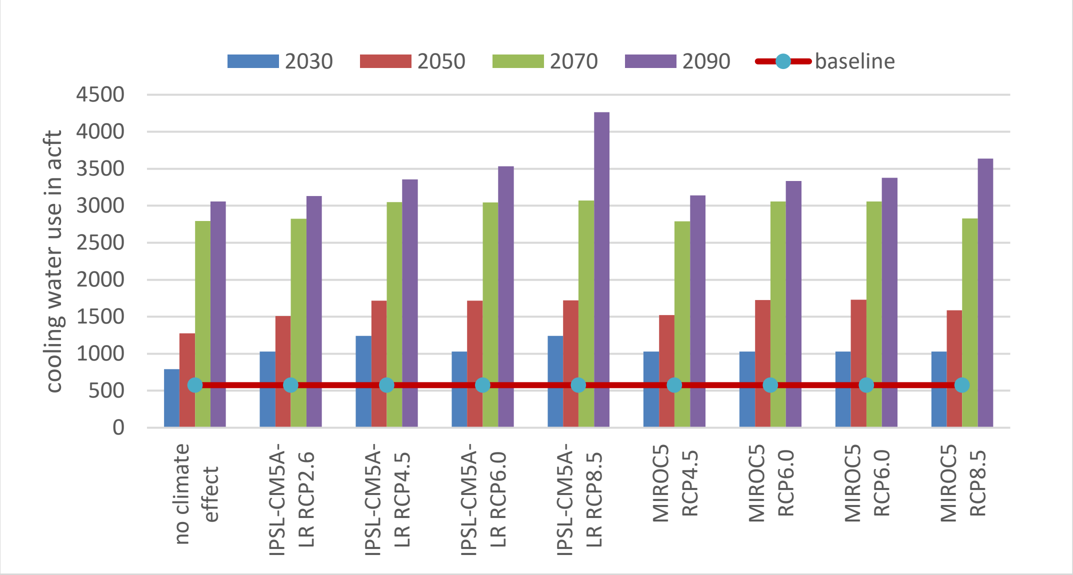


Figure 4.6 Water use by power plants under different scenarios

4.7.6. Power Plant Retrofits

EDSIMRGW_NEX includes the conversion of existing coal plants to burn natural gas, and retrofitting existing once-through cooling systems or recirculating systems to dry cooling systems. Allowing natural gas firing in a coal boiler typically involves boiler modification cost, EDSIMRGW_NEX results show none of coal fired power plant modified boilers.

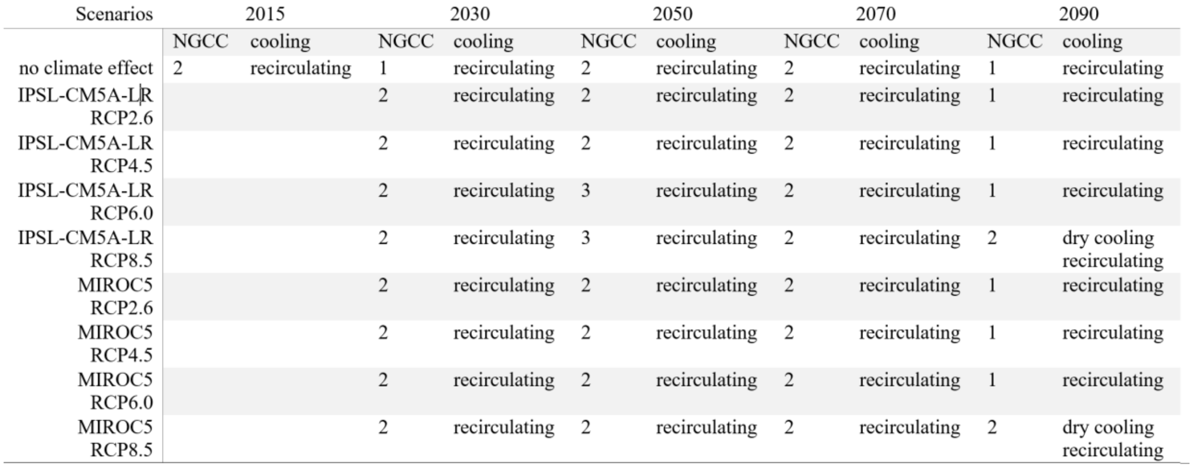
Table 4.9 shows the results of cooling system retrofits in all scenarios, there are 12 plants (11 natural gas plants and 1 petroleum refinery) in the region retrofit cooling systems, among them 9 plants retrofit cooling systems in the baseline scenario, one of them retrofit once-through cooling systems to recirculating cooling systems, all others retrofit recirculating systems to dry cooling systems.

Table 4.9 Power plants cooling retrofits in all scenarios

Scenarios	2015	2030	2050	2070	2090
no climate effect	9		2	1	
IPSL-CM5A-LR RCP2.6		2			
IPSL-CM5A-LR RCP4.5		2			1
IPSL-CM5A-LR RCP6.0		1	1		1
IPSL-CM5A-LR RCP8.5		2			1
MIROC5 RCP2.6		1	1		1
MIROC5 RCP4.5		2			1
MIROC5 RCP6.0		2			1
MIROC5 RCP8.5		2			1

EDSIMRGW_NEX makes a tradeoff between the surface water availability and the retrofitted cost. As power plant use surface water for cooling purpose, if cooling water use exceed the upper diversion amount of surface water right, plants retrofit recirculating cooling systems to dry cooling systems or retrofit once-through cooling systems to recirculating systems. Most power plants retrofit cooling systems in the baseline scenario when there is no climate change effect and no population growth effect, and the retrofitted decades for other plants depend on the climate scenarios. Table 4.10 shows new plants are built with recirculating cooling systems in most scenarios, plants with dry cooling systems are built in 2090 under extreme RCP cases (RCP8.5) when drought condition induce difficulty in obtaining sufficient cooling water.

Table 4.10 Cooling systems of new power plants



Scenarios	2015		2030		2050		2070		2090	
	NGCC	cooling	NGCC	cooling	NGCC	cooling	NGCC	cooling	NGCC	cooling
no climate effect	2	recirculating	1	recirculating	2	recirculating	2	recirculating	1	recirculating
IPSL-CM5A-LR RCP2.6			2	recirculating	2	recirculating	2	recirculating	1	recirculating
IPSL-CM5A-LR RCP4.5			2	recirculating	2	recirculating	2	recirculating	1	recirculating
IPSL-CM5A-LR RCP6.0			2	recirculating	3	recirculating	2	recirculating	1	recirculating
IPSL-CM5A-LR RCP8.5			2	recirculating	3	recirculating	2	recirculating	2	dry cooling recirculating
MIROC5 RCP2.6			2	recirculating	2	recirculating	2	recirculating	1	recirculating
MIROC5 RCP4.5			2	recirculating	2	recirculating	2	recirculating	1	recirculating
MIROC5 RCP6.0			2	recirculating	2	recirculating	2	recirculating	1	recirculating
MIROC5 RCP8.5			2	recirculating	2	recirculating	2	recirculating	2	dry cooling recirculating

4.7.7. Welfare Effects

Under 2015 conditions, consumers' surplus in electricity sector is $3.41 billion and cost is $1.1 billion, and net benefit from electricity sector is $2.31 billion. Table 4.11 - 4.13 present consumers’ surplus, total cost, and welfare percentage changes with and without climate change effects, the total cost includes cooling systems retrofit cost, boiler retrofit cost, annualized capital cost of building new power plants, fixed operating cost, cooling water cost, and fuel cost.

Table 4.11 Percentage change of consumers’ surplus

Scenarios	2030	2050	2070	2090
	percentage change from baseline			
no climate effect	14.74	36.24	60.35	89.11
IPSL-CM5A-LR RCP2.6	21.31	44.45	70.14	100.49
IPSL-CM5A-LR RCP4.5	23.02	47.68	75.94	109.94
IPSL-CM5A-LR RCP6.0	21.81	49.38	77.52	109.68
IPSL-CM5A-LR RCP8.5	21.94	52.89	88.63	136.81
MIROC5 RCP2.6	20.20	42.68	67.81	100.09
MIROC5 RCP4.5	22.01	44.73	74.36	105.09
MIROC5 RCP6.0	20.32	45.25	73.58	106.55
MIROC5 RCP8.5	21.16	48.14	83.33	122.70

Table 4.12 Percentage change of cost

	2030	2050	2070	2090
Scenarios	percentage change from baseline			
no climate effect	-10.50	-4.33	2.21	18.60
IPSL-CM5A-LR RCP2.6	-19.93	-19.36	-13.30	2.50
IPSL-CM5A-LR RCP4.5	-19.41	-17.22	-6.99	11.73
IPSL-CM5A-LR RCP6.0	-21.03	-12.71	-11.92	2.89
IPSL-CM5A-LR RCP8.5	-21.23	-9.92	-2.15	36.00
MIROC5 RCP2.6	-12.82	-11.15	-5.89	10.55
MIROC5 RCP4.5	-16.24	-15.03	-3.55	13.84
MIROC5 RCP6.0	-18.99	-15.03	-4.66	14.07
MIROC5 RCP8.5	-18.23	-12.79	4.52	27.66

Table 4.13 Percentage change of welfare

	2030	2050	2070	2090
Scenarios	percentage change from baseline			
no climate effect	26.66	55.40	87.79	122.40
IPSL-CM5A-LR RCP2.6	40.78	74.58	109.54	146.75
IPSL-CM5A-LR RCP4.5	43.06	78.32	115.10	156.31
IPSL-CM5A-LR RCP6.0	42.03	78.70	119.75	160.10
IPSL-CM5A-LR RCP8.5	42.32	82.54	131.49	184.40
MIROC5 RCP2.6	35.79	68.10	102.60	142.37
MIROC5 RCP4.5	40.07	72.94	111.14	148.17
MIROC5 RCP6.0	38.89	73.71	110.52	150.21
MIROC5 RCP8.5	39.76	76.91	120.54	167.57

First, we look at the results of considering population growth, for example, no climate change in 2030, the results show that consumers' surplus increases 14.74 percent compared to baseline, that is a gain of $0.5 billion of the base year; total cost is 10.5 percent less than the base year, since most of cooling retrofits take place in 2015, the net benefit increases 26.66 percent compared to the base year. If demand for electricity rises further, that is, no climate change scenario in 2050, 2070, and 2090, consumers' surplus increases by 36.24 percent, 60.35 percent and 89.11 percent respectively; cost is 4.33 percent lower in 2050 relative to baseline scenario, but increases by 2.21 percent and 18.6 percent in 2070 and 2090 respectively, because electricity demand keeps increasing, the region needs to add power supply capacity in order to meet electricity demand, building and operating new power plants add more cost in late decades; net benefit under no climate change scenario is gradually increasing from year 2030 to 2090.

Then we look at the welfare changes under climate change scenarios. Overall, two climate models under RCP2.6, RCP4.5, RCP6.0 and RCP8.5 report consistently increase in net benefit. The net benefit increases in the range of 35.79% to 43.06% relative to the baseline across 8 climate change scenarios in 2030; and it further increases in the range of 142.37% to 184.4% in 2090. Consumers' surplus in IPSL-CM5A-LR is greater than that in MIROC5 under the same emission scenario, since electricity demand is higher in drier condition. In the decades between 2030 to 2070, the total cost in the 8 climate change scenarios is lower compare to that in 2015, since most of the retrofits take place in 2015, but this number increases in 2090, since coal fired power plants begin to operate in 2090 in order to meet the electricity demand, yielding more fuel cost, meanwhile, the region builds new NGCCs with dry cooling systems also increase the total cost.

4.8. Conclusion

This study does a FEW Nexus evaluation with emphasis on electricity generation sector in South Central Texas as it is influenced by increasing populations and climate change. Population growth and climate change substantially increase electricity demand, power plant supply capacity, and cooling water use. In particularly, the region adds power supply capacity from 2030 to 2090 in order to meet the growing demand for electricity including demands from water supply projects. Comparing all climate scenarios, higher temperature and less precipitation induce cooling water use increases.

In terms of net benefit in energy sector, population growth and climate change increase net benefit in the projection period. Higher temperature and growing population in the region increase consumers' surplus due to increasing demand in electricity. The total cost decreases at earlier projection periods due to retrofits have taken place in 2015, and experiences increasing beginning in 2090, as electricity demand in 2090 put more power plants in operation.

This study generates information on power plant operation and retrofits by considering FEW Nexus as a system. Such information can help stakeholders make decisions on whether to retrofit boiler or cooling systems of power plants, whether to build new plants, and manage water resources under climate change conditions.

5. CONCLUSIONS

Decision makers can benefit from information on FEW Nexus wide implications of actions including information on resource use, commodity flows, environmental effects, and future resource availability. With knowledge of benefits and costs across different sectors, decision makers can decide what alternatives to pursue and gain insight on needs for implementation.

This dissertation generates information on water savings via electrical energy cooling system retrofits and on the impacts of population growth and climate change on the electricity sector in the full context of FEW Nexus. Growing populations and climate change will have significant effects on wholesale electricity prices and electricity demand. Decision makers will need to be aware of these effects. This dissertation reports on parts of these issues in a FEW Nexus case study in South Central Texas.

Chapter 2 provides background on the study region including aquifers, river basins, TWDB water projects, climate conditions, agriculture, and electricity. It also reviews major economic issues when considering potential FEW Nexus actions. This chapter reveals theoretical concepts and grounds them in practical FEW Nexus domains to illustrate why considerations of these concepts are essential.

Chapter 3 reports on an economic investigation of cooling options as a potential way of releasing water for other uses. The estimated costs per acre foot of water saved for retrofitting existing recirculating systems to dry cooling systems were found to be generally higher than most of the current water projects under regional consideration, only being competitive with high cost projects. We do find the estimated costs for installing dry cooling in new power plants are lower because one just needs the marginal costs of the alternative cooling technology and does not need to remove old equipment or manipulate the existing system to accommodate new equipment. When we consider climate change, cooling water use increases, dry cooling retrofits are less costly.

Chapter 4 generates information on FEW Nexus decisions with emphasis on electricity sector under increasing population and climate change conditions. We examine the effects of population growth and climate change on electricity demand, wholesale electricity price, power plant supply capacity, cooling water use, cooling and boiler retrofits, and welfare. We find that this region will need to add power supply capacity from 2030 to 2090 in order to meet population and climate stimulated growing demands for electricity. When comparing cooling water use in all climate scenarios, we observe higher temperatures and less precipitation cause cooling water increases. Our model indicates it would be desirable to retrofit cooling systems in 12 power plants, and most of them retrofit cooling systems in the baseline scenario when there is no climate change and no population growth effect. We also find that growing population and climate change increase power consumer welfare in the projection period.

This study has a number of limitations that could be improved upon in further research. First, a broader geographic spatial-analogue approach could be used to estimate climate effects on cooling water consumptive use. We use power plants in South Central Texas to estimate climate impact on cooling water use, but it is limited by the number of plants and their characteristics. Statewide or broader scale data could be used. Second, we use Edwards Aquifer recharge to define 9 state of nature in the region. However, future work needs to better define states of nature based on broader weather, surface water and aquifer recharge conditions across the region. Third, we use county level wind speed and monthly solar radiation to estimate per unit wind and solar based electricity generation, such assumption might not hold when climate change is factored in, thus solar radiation and wind speed will be adjusted under future climate change scenarios, which could be addressed in future work. Last, we assume power plants take fresh water for cooling purpose without consideration of degraded quality, saline water. We do this on the assumptions that saline water would damage the cooling systems, and the high cost to process salt concentration. However, to accommodate limited fresh surface water in the future, we may add the possibility of using non-traditional water for cooling in future work.

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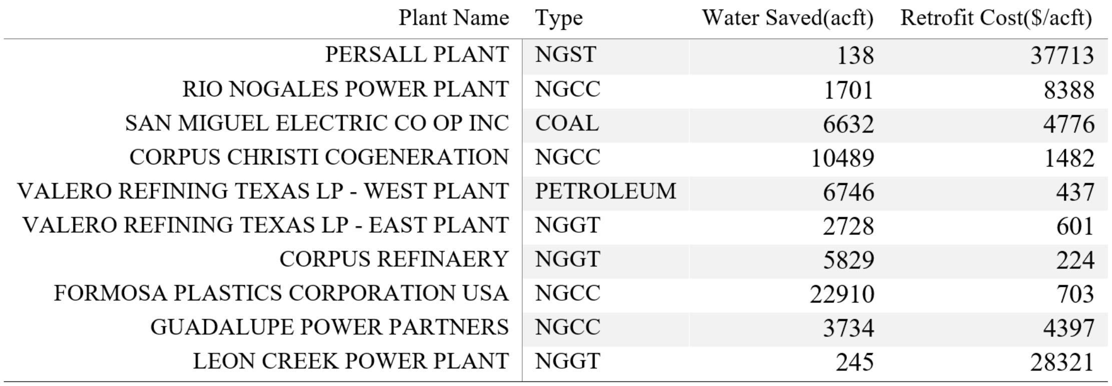
APPENDIX A

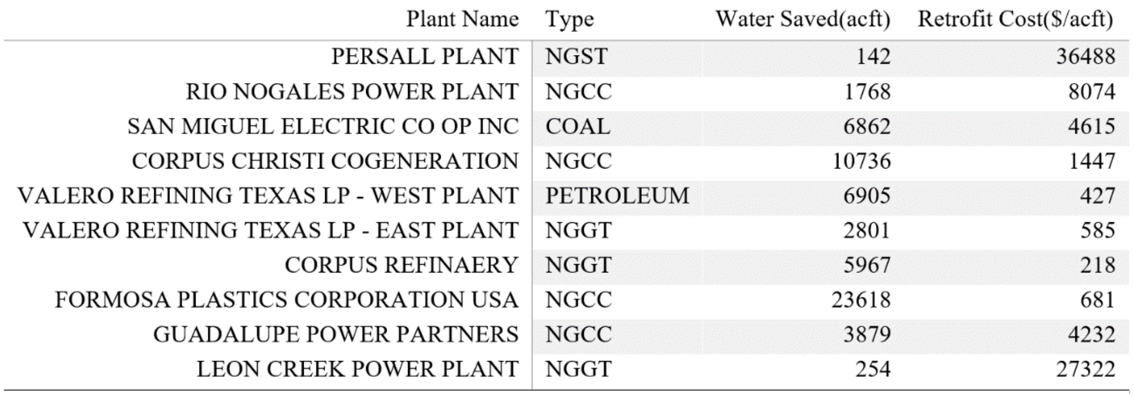
RETROFIT COST FOR ALL POWER PLANTS

Table A1 Retrofit cost in 2050 under RCP 2.6



Plant Name	Type	Water Saved(acft)	Retrofit Cost($/acft)
PERSALL PLANT	NGST	138	37713
RIO NOGALES POWER PLANT	NGCC	1701	8388
SAN MIGUEL ELECTRIC CO OP INC	COAL	6632	4776
CORPUS CHRISTI COGENERATION	NGCC	10489	1482
VALERO REFINING TEXAS LP - WEST PLANT	PETROLEUM	6746	437
VALERO REFINING TEXAS LP - EAST PLANT	NGGT	2728	601
CORPUS REFINAERY	NGGT	5829	224
FORMOSA PLASTICS CORPORATION USA	NGCC	22910	703
GUADALUPE POWER PARTNERS	NGCC	3734	4397
LEON CREEK POWER PLANT	NGGT	245	28321

Table A2 Retrofit cost in 2050 under RCP 4.5



Plant Name	Type	Water Saved(acft)	Retrofit Cost($/acft)
PERSALL PLANT	NGST	142	36488
RIO NOGALES POWER PLANT	NGCC	1768	8074
SAN MIGUEL ELECTRIC CO OP INC	COAL	6862	4615
CORPUS CHRISTI COGENERATION	NGCC	10736	1447
VALERO REFINING TEXAS LP - WEST PLANT	PETROLEUM	6905	427
VALERO REFINING TEXAS LP - EAST PLANT	NGGT	2801	585
CORPUS REFINAERY	NGGT	5967	218
FORMOSA PLASTICS CORPORATION USA	NGCC	23618	681
GUADALUPE POWER PARTNERS	NGCC	3879	4232
LEON CREEK POWER PLANT	NGGT	254	27322

Table A3 Retrofit cost in 2050 under RCP 6.0

Plant Name	Type	Water Saved(acft)	Retrofit Cost($/acft)
PERSALL PLANT	NGST	137	38004
RIO NOGALES POWER PLANT	NGCC	1684	8473
SAN MIGUEL ELECTRIC CO OP INC	COAL	6584	4810
CORPUS CHRISTI COGENERATION	NGCC	10458	1486
VALERO REFINING TEXAS LP - WEST PLANT	PETROLEUM	6726	438
VALERO REFINING TEXAS LP - EAST PLANT	NGGT	2735	599
CORPUS REFINAERY	NGGT	5812	224
FORMOSA PLASTICS CORPORATION USA	NGCC	22781	707
GUADALUPE POWER PARTNERS	NGCC	3697	4441
LEON CREEK POWER PLANT	NGGT	243	28618

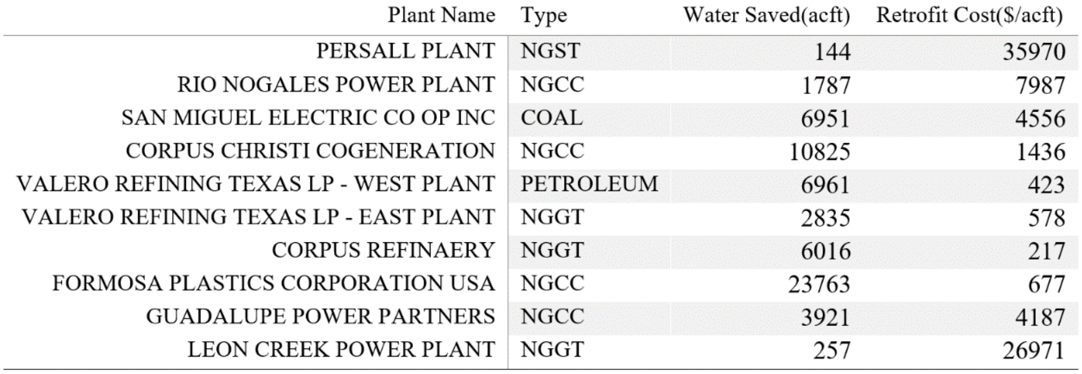
Table A4 Retrofit cost in 2050 under RCP8.5

Plant Name	Type	Water Saved(acft)	Retrofit Cost($/acft)
PERSALL PLANT	NGST	143	36339
RIO NOGALES POWER PLANT	NGCC	1772	8054
SAN MIGUEL ELECTRIC CO OP INC	COAL	6887	4599
CORPUS CHRISTI COGENERATION	NGCC	10783	1441
VALERO REFINING TEXAS LP - WEST PLANT	PETROLEUM	6934	425
VALERO REFINING TEXAS LP - EAST PLANT	NGGT	2821	581
CORPUS REFINAERY	NGGT	5993	218
FORMOSA PLASTICS CORPORATION USA	NGCC	23653	680
GUADALUPE POWER PARTNERS	NGCC	3889	4222
LEON CREEK POWER PLANT	NGGT	255	27222

Table A5 Retrofit cost in 2090 under RCP 2.6

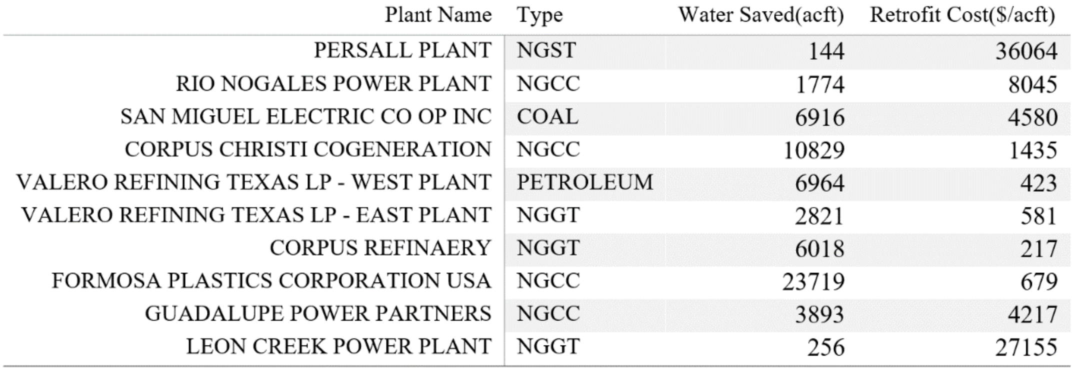
Plant Name	Type	Water Saved(acft)	Retrofit Cost($/acft)
PERSALL PLANT	NGST	145	35713
RIO NOGALES POWER PLANT	NGCC	1797	7941
SAN MIGUEL ELECTRIC CO OP INC	COAL	6997	4527
CORPUS CHRISTI COGENERATION	NGCC	10924	1423
VALERO REFINING TEXAS LP - WEST PLANT	PETROLEUM	7025	419
VALERO REFINING TEXAS LP - EAST PLANT	NGGT	2857	574
CORPUS REFINAERY	NGGT	6071	215
FORMOSA PLASTICS CORPORATION USA	NGCC	23950	672
GUADALUPE POWER PARTNERS	NGCC	3944	4162
LEON CREEK POWER PLANT	NGGT	259	26824

Table A6 Retrofit cost in 2090 under RCP4.5



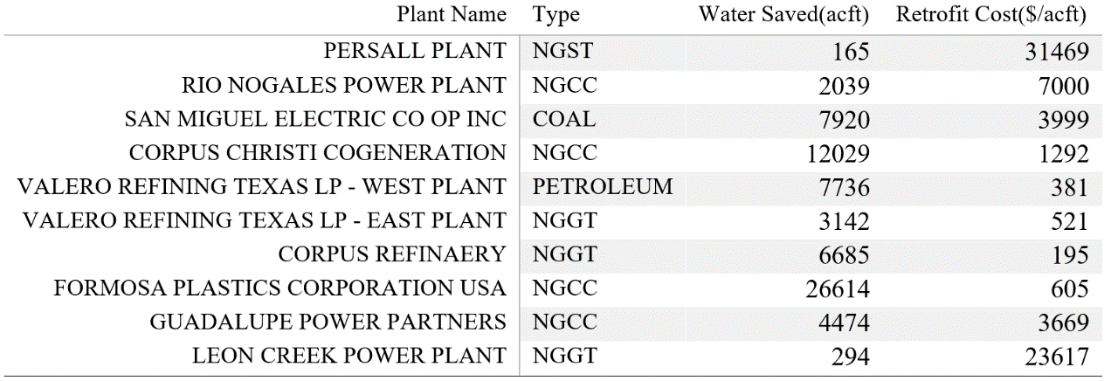
Plant Name	Type	Water Saved(acft)	Retrofit Cost($/acft)
PERSALL PLANT	NGST	144	35970
RIO NOGALES POWER PLANT	NGCC	1787	7987
SAN MIGUEL ELECTRIC CO OP INC	COAL	6951	4556
CORPUS CHRISTI COGENERATION	NGCC	10825	1436
VALERO REFINING TEXAS LP - WEST PLANT	PETROLEUM	6961	423
VALERO REFINING TEXAS LP - EAST PLANT	NGGT	2835	578
CORPUS REFINAERY	NGGT	6016	217
FORMOSA PLASTICS CORPORATION USA	NGCC	23763	677
GUADALUPE POWER PARTNERS	NGCC	3921	4187
LEON CREEK POWER PLANT	NGGT	257	26971

Table A7 Retrofit cost in 2090 under RCP6.0



Plant Name	Type	Water Saved(acft)	Retrofit Cost($/acft)
PERSALL PLANT	NGST	144	36064
RIO NOGALES POWER PLANT	NGCC	1774	8045
SAN MIGUEL ELECTRIC CO OP INC	COAL	6916	4580
CORPUS CHRISTI COGENERATION	NGCC	10829	1435
VALERO REFINING TEXAS LP - WEST PLANT	PETROLEUM	6964	423
VALERO REFINING TEXAS LP - EAST PLANT	NGGT	2821	581
CORPUS REFINAERY	NGGT	6018	217
FORMOSA PLASTICS CORPORATION USA	NGCC	23719	679
GUADALUPE POWER PARTNERS	NGCC	3893	4217
LEON CREEK POWER PLANT	NGGT	256	27155

Table A8 Retrofit cost in 2090 under RCP8.5



Plant Name	Type	Water Saved(acft)	Retrofit Cost($/acft)
PERSALL PLANT	NGST	165	31469
RIO NOGALES POWER PLANT	NGCC	2039	7000
SAN MIGUEL ELECTRIC CO OP INC	COAL	7920	3999
CORPUS CHRISTI COGENERATION	NGCC	12029	1292
VALERO REFINING TEXAS LP - WEST PLANT	PETROLEUM	7736	381
VALERO REFINING TEXAS LP - EAST PLANT	NGGT	3142	521
CORPUS REFINAERY	NGGT	6685	195
FORMOSA PLASTICS CORPORATION USA	NGCC	26614	605
GUADALUPE POWER PARTNERS	NGCC	4474	3669
LEON CREEK POWER PLANT	NGGT	294	23617