OPTIMAL WATER ALLOCATION PLANNING USING
A WATER-ENERGY-FOOD NEXUS APPROACH:
THE CASE OF MATAGORDA COUNTY, TX

A Thesis

by

MUHAMMED IMRAN KULAT

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Chair of Committee,	Rabi H. Mohtar
Committee Members,	Francisco Olivera
	Clyde Munster
Head of Department,	Robin Autenrieth

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ABSTRACT

Conventional methods for analyzing the influences of water planning decisions frequently miss the dynamic interconnections between water, energy, and food (WEF) resources. This study presents a platform to analyze the feasibility of possible interventions and recommend scenarios to enhance WEF resource sustainability. A water-centric framework includes a unique analytic tool for quantification of the tradeoffs for future scenarios consisting of interventions, and a sustainability analysis for drawing recommendations for future water allocation in light of WEF inter-linkages. The applied case is Matagorda County, which, despite ample water resources, is considered one of the most water stressed area of Texas due to high demands on water resources from agriculture and energy sectors.

The possible interventions mostly include water-related infrastructure such as building desalination plant, treatment facility, improving existing canal system, applying high-tech on-farm irrigation, changing cooling system of the nuclear plant, and building their conveyance systems. A great number of scenarios consisting of combinations of possible interventions are developed. The analytic tool produces quantitative parameters for each scenario. A sustainability analysis using the parameters produced by the tool enables presentations of advisable water, energy, food, environment, or cost -centric and optimal scenarios. The findings of the study present most sustainable combinations of water-related infrastructure that can protect primary resources as well as contribute economic well-being of Matagorda County.

DEDICATION

To my wonderful wife Memduha Begum

and

Our daughter, Meryem.

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NOMENCLATURE

WEF	Water, energy, and Food
TWDB	Texas Water Development Board
FAO	Food and Agriculture Organization of the United Nations
SEI	Stockholm Environment Institute
GWSP	Global Water System Project
SDG	Sustainable Development Goals
IEA	International Energy Agency
DOE	Department of Energy of United States
WWDR	World Water Assessment Programme, United Nations
OECD	The Organisation for Economic Co-operation and Development
IWRM	Integrated Water Resource Management
GWP	Global Water Partnership
MCA	Multi Criteria Analysis
TCEQ	Texas Commission on Environmental Quality
TPWD	Texas Park and Wildlife Department
MCEDC	Matagorda County Economic Development Corporation
TNRIS	Texas Natural Resources Information System
NOAA	National Oceanic and Atmospheric Administration
NCDC	National Climatic Data Center
MRLC	Multi-Resolution Land Characteristics Consortium
USDA	Department of Agriculture of United States

LCRA	Lower Colorado River Authority
USGS	United States Geological Survey
STP	South Texas Project
STPNOC	South Texas Project Nuclear Operation Company
EIA	U.S. Energy Information Administration
RRC	Railroad Commission of Texas
AGI	American Geosciences Institute
MCR	Main Cooling Reservoir
NASS	National Agricultural Statistics Service
ERS	Economic Research Service
USNCR	United States Nuclear Regulatory Commission
IAEA	International Atomic Energy Agency
CPGCD	Coastal Plains Groundwater Conservation District
B/CS	Bryan/College Station
HSUS	Humane Society of the United States
P	Pressure
T	Time
TVA	Tennessee Valley Authority
TxDOT	Texas Department of Transportation
W	Water
E	Energy
F	Food Produced

R	Revenue from Food
C	Cost
CO2	Carbon-dioxide emission
L	Land Area
Wf	Weighting Factors
NREL	National Renewable Energy Laboratory
SAM	System Advisor Model
USBR	United States Bureau of Reclamation
UGA	University of Georgia
A&M	Agricultural and Mechanical
M&I	Municipal and Industrial
EPRI	Electric Power Research Institute

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1. INTRODUCTION

Under the entwined influences of population rise, climate change, urbanization, and environmental deterioration, various water issues emerge at the global arena. Nations, particularly developed nations with established water infrastructure systems, have begun to consider more efficient management strategies and improved infrastructures in the face of anticipated increased demands for water. Conventional engineering and management decision making processes for water resources tend to consider cost and quantity water parameters. However, achieving optimal and sustainable water allocation and management decisions demand a holistic approach; one that considers all stakeholders and observers and which takes into account the costs of energy production, food production, and the environment due to the interdependencies of primary resources.

This study intends to establish a water-energy-food (WEF) nexus based analytical framework to quantify the tradeoffs between the various tenants of the nexus considering multiple interventions across ranges of water consumers. The case selected for the study is Matagorda County: once famous for its lucrative rice farms. However, recent water shortages have caused dramatic shifts in its cropping patterns. Matagorda County is also home to one of two nuclear power plants in Texas, which consumes approximately one-third of Matagorda's existing water supplies. Recently issued licenses will more than double energy production from the plant and will further exacerbate the remaining natural resources of the county. Keep in mind that there are also other external factors that need to be accounted such as rise in population, climate change, urbanization, and rising energy demands. Thus, consideration of the tradeoffs involved is critical for sustainable management of the primary resources as we face the growing water gap, today and into the future.

This study is devoted to bringing optimal water allocation analysis: feasible scenarios to calculate this optimum in light of other primary resource demands and constraints (environmental, financial) are considered. In doing so, possible interventions to mitigate water stress in the region are determined, which are mostly water-related infrastructure systems. The scenarios consisting of possible interventions are developed to be input to a WEF nexus tool that analyze interconnections and produces the quantitative results for each scenario. A sustainability analysis is carried out using the data produced by the tool to present water-centric, food-centric, energy-centric, environment-centric, cost-centric, and all-equal (optimum) scenario. During the analysis, the preferences of the stakeholders are reflected. Therefore, water managers, planners, stakeholders, and other observers will be able to utilize the outcomes of the study, depending upon their demand perspectives. Policy makers will also have opportunity to decide optimal, sustainable, and holistic water allocation which analytically takes multiple perspectives into account. Conclusions are drawn and recommendations offered based upon the identification of the causes of water stress, enabling future mitigation of water stresses considering WEF inter-linkages.

1.1 The Problem

Texas Water Development Board (TWDB), one of the major water-related agency of Texas, is in charge of state-wide water planning. TWDB presents water plans at each 5-year planning cycle. According to the draft edition of the 2017 State Water Plan (TWDB-2017), which is the recent available water plan, Matagorda County is expected to face a shortage of 191,911 acre-feet in the year of 2020. Therefore, Matagorda County is considered one of the most water stressed county among 254 counties of Texas.

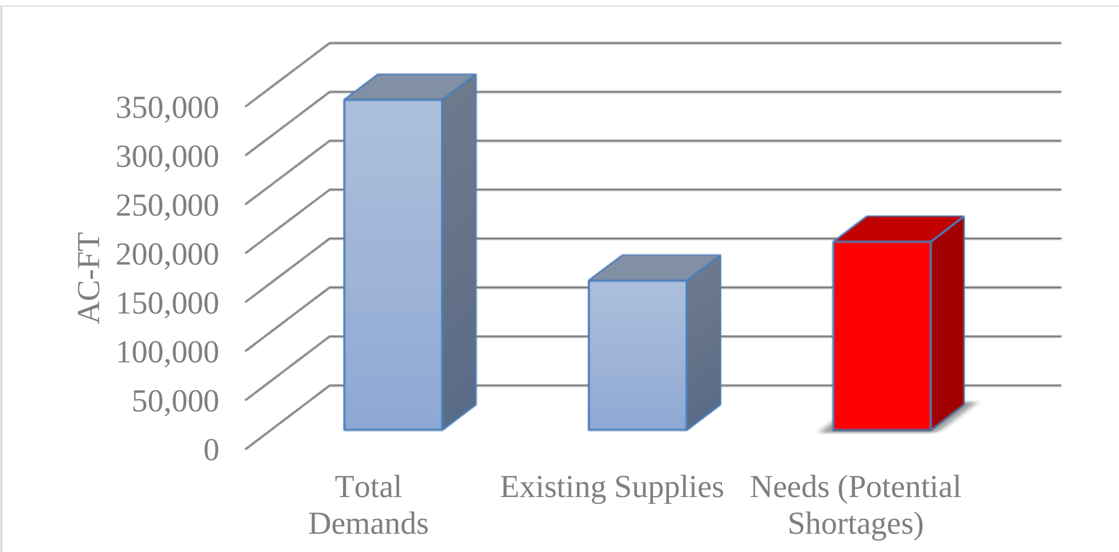

Figure 1. Matagorda County Potential Water Needs in 2020 According to TWDB (Data Source: TWDB-2017)

The column indicating total water demands in Figure 1 is due primarily to irrigation requirements and steam-electric production, with 62% and 31% of total water demand of the county respectively (TWDB, 2016a). These two industries are crucial for the economy of Matagorda County and are not expected to fade away in the foreseeable future. Irrigation and steam-electric production seem cornerstones of two of the components of the water-energy-food nexus. Both sectors are dependent on water for their operations and contribute to the water stresses faced by the county currently and well into the future. Figure 2 provides detailed information about projected water demands by Sectors.

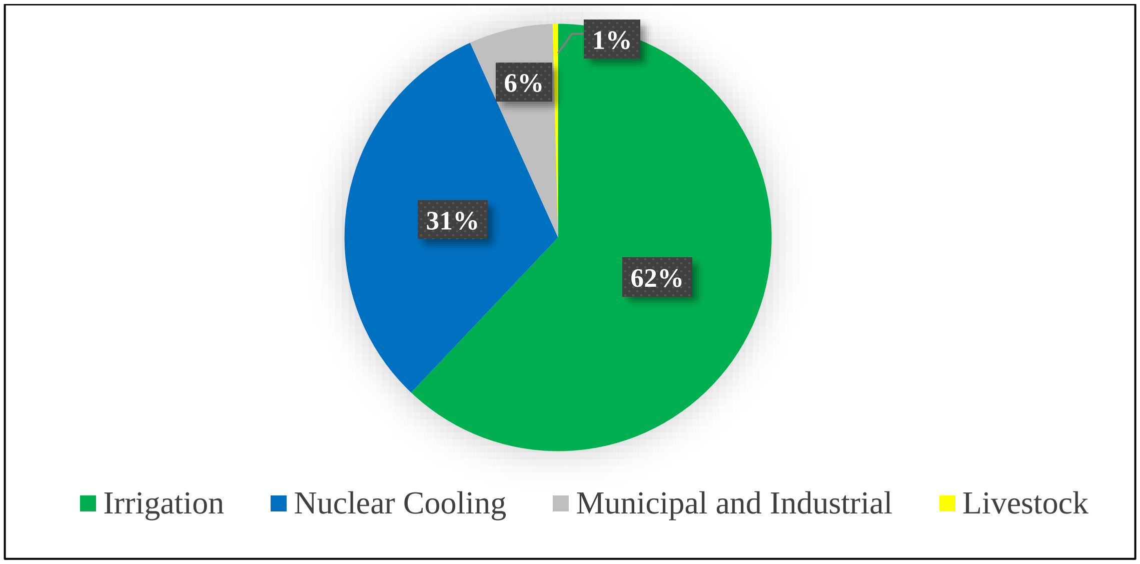

Figure 2. Water Demands in 2020 by Sectors, (Data Source: TWDB-2017)

A significant shortfall is expected to continue throughout the planning time frame of the state water plan as shown in Table 1 below (TWDB, 2016a).

Year	Potential Shortages (acre-feet)
2020	191,911
2030	186,220
2040	180,692
2050	175,320
2060	170,093
2070	164,999

Table 1. Matagorda County Potential Water Shortages 2020-2070 (Data Source: TWDB-2017)

1.2 Research Objectives

The goal of this study is to identify the reasons that cause water stress in Matagorda County and to develop a unique WEF Nexus model, which provides scenarios to draw sustainable recommendations for the future to mitigate stress in water sustainability considering water-energy-food inter-linkages. This study also intends to build a water-centric framework which help water-related infrastructure project selection process of decision makers and policy makers. In this respect, the research question and the primary objectives can be seen below:

Research Question

How does the Water – Energy – Food Nexus approach help in water-related infrastructure decisions to mitigate water stresses in Matagorda County?

Objectives

I. Develop a systems level water – energy- food nexus platform and tool to assess tradeoffs in water planning scenarios in Matagorda County

II. Identify feasible interventions that can mitigate risk and vulnerability in the primary resources (water, energy, food) for Matagorda County.

III. Draw recommendations for future water allocations in Matagorda County, based on economic, social and environmental sustainability and the tradeoff implications for energy and food resources.

Matagorda County is for a well-suited case study for the water-energy- food nexus because of its current and projected water shortages, water demands for nuclear power production, and water demands for agricultural production. The boundaries of Matagorda County contain all the elements necessary to compose and analyze a nexus system.

2. LITERATURE AND BACKGROUND

2.1 Main Concept

"Water, energy, and food are three highly connected systems. The ability to face the current and anticipated global challenges will be governed by the ability of better understanding the interconnectedness and tradeoffs between these systems. Higher levels of collaboration between governmental entities concerned in setting future resource management strategies and policies are thus a must." (Mohtar & Daher, 2012) .

Before disclosure of a nexus model framework that allows to discover and apprehend the interlinkages between water, energy and food (WEF) systems, the pioneered previous works in the area of WEF nexus and current and anticipated agenda need to be reviewed. Not only does this chapter focuses on the background of WEF Nexus approach which has been paid attention increasingly in the scientific community, it also explores regional primary resource sustainability considerations. The background of the case study is included as well.

2.2 Water – Energy – Food Nexus and Definitions

"A Nexus approach helps us to better understand the complex and dynamic interrelationships between water, energy and food, so that we can use and manage our limited resources sustainably. It forces us to think of the impacts a decision in one sector can have not only on that sector, but on others. Anticipating potential trade-offs and synergies, we can then design, appraise and prioritize response options that are viable across different sectors." (FAO, 2014c)

2.2.1 Background of Water-Energy-Food Nexus

Global Risks report published by World Economic Forum in 2011 stated that when rapid increase in global population and the demand for welfare considered, the primary resources would be required to rise by approximately 30-50% in the upcoming a few decades. In addition, the report asserted that risks revolving around water-energy-food nexus were considered one of three crucial risk group that global community would face (Word Economic Forum, 2011). Although some definitions and recognitions regarding WEF nexus had begun earlier, the first documented overview of the nexus with the main lines was published as a background paper of Bonn 2011 Conference in the same year. The Bonn conference explicitly indicated that water, energy and food securities could be achieved by means of a nexus approach (SEI, 2011). Another milestone for the evaluation of the nexus was 'Sustainability in the Water-Energy-Food Nexus' conference [GWSP

2014] which addressed for an action to develop solid strategies presenting the nexus (Daher & Mohtar, 2015). After those rising awareness and scientific works, various discussions revolved around the sustainable development goals (known as SDGs) and possible contribution of the WEF nexus approach (Biggs, et al., 2015).

Tools are helpful to solve complex systems. The WEF systems along with their interconnected systems embraces many complexities. In this regard, various aspects of managing primary resources and the surrounding systems such as climate and ecosystem are presented in the existing tools (Daher & Mohtar, 2015). However, the need in supporting decision-makers in quantifying interconnections of the resources and identifying the sustainability of the management strategies led generation of first WEF Nexus tool as of October 2013 (Mohtar & Daher, 2013). The framework of the tool was food-centric (Daher, 2012). It nevertheless took into account energy and water securities as well as food security while finding solutions in the decision making and planning process (Daher & Mohtar, 2014).

2.2.2 Water - Energy Nexus

Using water to produce the energy needed and using energy to convey and treat water needed make energy and water resources intricately linked (Gleick, 1994). Almost all of the current energy production types including extraction (fossil fuels, nuclear raw materials and biofuels) and conversation processes require water use (Span, et al., 2014). Energy limitations such as availability, affordability and long term sustainability narrow down the water use. Also, limited water sets limit on production of energy. Thus, the understanding the linkages between two major resources will help meet requirements for each side (Gleick, 1994).

Water is an essential input for energy sector. The production process of energy resources does usually require water use. Among various energy productions, the most water-intense resource for energy are biodiesel and ethanol (IEA, 2012). As a matter of fact, thermoelectric power which compiled by cooling system is the largest water consumer in the US, with 33% of annual total water withdrawals (Maupin, et al., 2014). The information regarding water consumption by type of energy source can be seen in Figure 3 below.

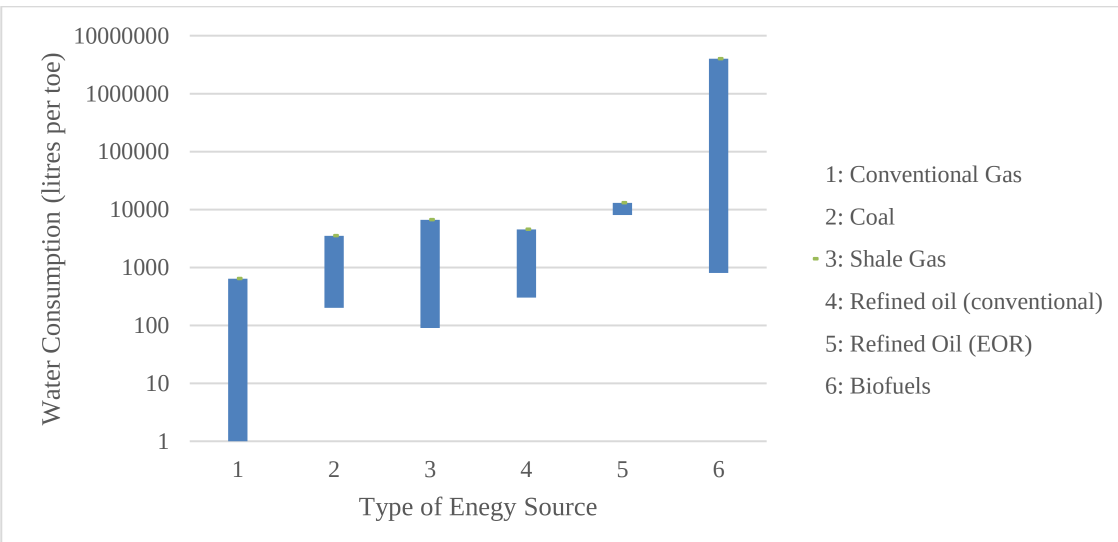

Figure 3. Water Consumptions in Energy Production. (Adapted from WEO-2012 Chapter 17 – Water for Energy (IEA, 2012))

Water supply, which requires power to withdraw, intake, transport, treat, desalinate water, is the other energy-water nexus component (IEA, 2012). Due to globally rising demand for water and limited freshwater resources which is only counted 2.5% of

Earth's total water (USGS, 2016b), the interests on the desalination are rising. However, desalination plants, considering todays technological advancement, require significant amount of capital cost along with energy cost during desalination process (TWDB, 2016a). In fact, desalinated water that is the most energy intensive water among water resources though the availability is very abundant. For instance, desalinating 1000-gallon sea water from Gulf of Mexico to make it drinkable requires 11.15 kWh energy (Desalination Committtee, 2011).

2.2.3 Water-Food Nexus

Food production (mainly agriculture) is the largest water consumer of freshwater resources in the world, with 70% of total freshwater withdrawals. Anticipated 70% food demand increase due to population rise by 2050s will put water and food security at risk (WWDR, 2014). In developed nations, water use pattern shows other usage types are more common than agricultural use unlike developing nations. Middle Eastern countries, for example, allocate 84% of total fresh water for agriculture whereas the portion in European countries is only 22% (FAO, 2014a). Despite the great number of agricultural water withdrawal in the world, the cultivated area under irrigation accounts only 21% which helps provide nearly half of the total food production. Besides, most of the agricultural lands in the world rely on precipitation (FAO, 2014b). Irrigation helps food producers to control production process and therefore increase efficiency. The vital importance of irrigation in ensuring food security and meeting with growing food demand can be seen in the Table 2 below (Singh, 2015).

Crop	Not irrigated (ton/acre)	Irrigated (ton/acre)	Yield increment (%)
Cotton	2.10	6.67	218
Rice	4.30	9.27	115
Beans	0.96	5.68	492
Corn	4.91	13.59	177
Soybean	4.56	7.41	163

Table 2. The Benefit of Irrigation on the Food Yield (Adapted from BAEN-464 Class Notes - Chapter 1 (Singh, 2015))

As the water for food is essentially vital, the main objective of irrigation is optimization while increasing the efficiency. This efficiency and adequacy through can be promoted through better management methodologies so that food security can be ensured without sacrificing net income and wasting water. It can be expected that, future optimization approaches will consider several disciplines including the issues of salinity, crop-water relations, new water resources and operational methods (English, et al., 2002). Quantification of the implication of new water use such as grey water and green water is a need to understand water-food relations. In particular, managing green water as described water comes from precipitation and turns back to the hydrologic cycle through evaporation is another key point in sustaining anticipated high future demands (Sloane, 2015).

2.2.4 Food – Energy Nexus

Agriculture as producer of food while planting and growing animals has dated back to around 12,000 years ago (National Geographic, 2016). Food production has boomed after the end of World War II thanks to spread of mechanizations all over the world, emerging new technologies, rising chemical pesticide and fertilizer use. In modern agriculture, replacing the labor demands with agricultural machines and maximizing the food production in the sector led soaring demand for energy, non-renewable energy in particular (Feenstra, et al., 2016).

In fact, historical values show that there is a complicated relationship between energy and food prices dependently (FAO, 2016) (EIA, 2016c). The Figure 4 below illustrates the relationship between oil and food prices since 1990.

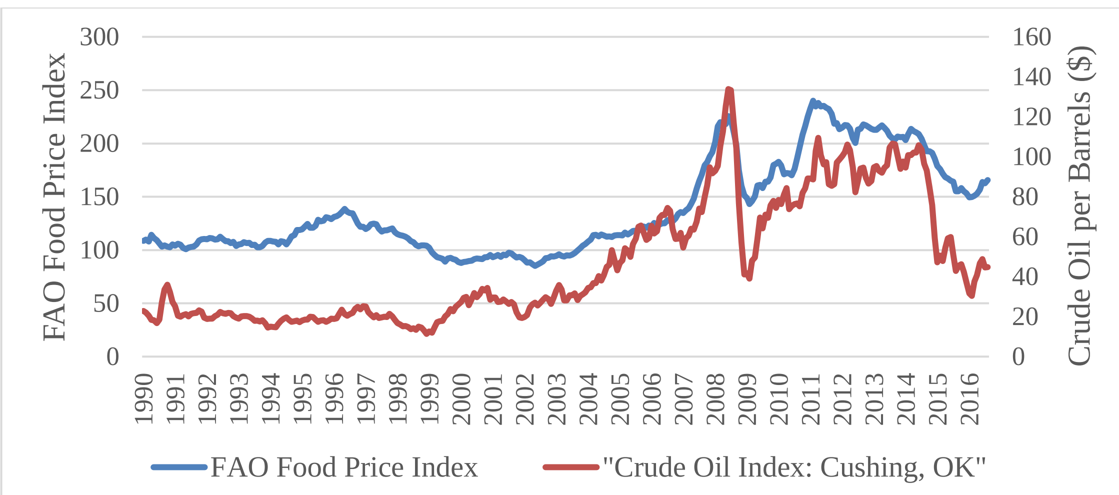

Figure 4. Historic Monthly Food Prices and Crude Oil per Barrel Indexes (Data for Indexes are from FAO and EIA (FAO, 2016) (EIA, 2016c))

Energy production has been becoming more dependent to food production. Recent technological improvements and policy actions have raised the demand for bioenergy despite the arguments on the sustainability level of bioenergy (Robledo-Abad, et al., 2016). Bioenergy production is directly linked with land use which is another limited source requiring an important consideration for the food-energy nexus (Chang, et al., 2016). FAO, in this regard, estimates that land area allocated for biofuels in 2020 will increase around 8 times more than the allocation in 2000 and reach to 35 million hectares globally (OECD - FAO, 2007).

2.3 Water Allocation Planning

Water, as one of the primary need of human being, has shaped the civilization of humankind. Accordingly, water infrastructure has history since the dawn of civilization. Throughout history, lack of fresh water supply and sanitation resulted diseases, poverty, migrations, deaths, changes in demography. Once humans had challenges to access direct fresh water resources, they either migrated to water abundant valleys or tried to find local solutions such as water conveyance from surface water resources or withdrawal from underground (Hassan, 2003) (BBC News, 2009).

2.3.1 Systems Thinking: A Solution to Complexity

Ancient large societies in North Africa, Asia, Middle East were established next to fresh water resources, mainly rivers, to access water easily for domestic, irrigation, and livestock purposes (National Research Council, 2002) . When it came to the industrial revolution and its indirect effects such as population boom and raised in life standards emerged new demands for water use due to industrial production process, energy production, and mining. The developments in material science such as cast iron and affordable concrete along with being able to use pumping technologies made enable to convey water much more easily. Therefore, the quantity of water use started to increase dramatically (Duffy, 2013). In the meantime, sharp rise in complexities in not only water resources but also other management required branches such as education, military, and economy took scientific communities' attention to systems theory and thinking. As long as the complex systems surrounding the life in the world are growing rapidly along with the effects of globalization and technological advancement, several definitions have been proposed for the definition of systems the in the scientific community (Arnold & Wade, 2015). Systems thinking which formed systems theory is a holistic approach to analyze and solve the complex issues while considering effective parameters and components at different levels with regard to the relationship of the whole (Meadows, 2008). As for building more sustainable future, systems thinking constituting of three major pillars of sustainability: economic pillar, social pillar, environmental pillar provide better understanding (Cattano, et al., 2011).

After World War II in particular, systems thinking approaches were increasingly applied to real life cases and used to define components of systems, their interrelationships, and analyze complex problems (Steven, 2002) . Wurbs and James describes the characteristics of systems analysis, [on which the WEF nexus approach has also been built (Sloane, 2015)], in water resources planning and management in the Table 3 (Wurbs & James, 2002b).

✓	Systematic quantitative approach to determining the optimum solutions to complex systems
✓	Decision-making support
✓	Comprehensive integrated systems focus
✓	Interdisciplinary aspects
✓	Reliance on mathematical models and computers

Table 3. Characteristics of Systems Analysis for Water Planning and Management (Reprinted from a book entitled "Water Resources Engineering" (Wurbs & James, 2002b))

2.3.2 Water Resources Systems Process and Development

2.3.2.1 Definitions and Concepts

Water management and planning varies with the sectors utilizing the water resource: irrigation, domestic water supply and sanitation, hydropower, navigation, environmental management (i.e. wastewater management, collection, treatment, disposal), storm water management, flood mitigation, erosion control (Wurbs & James, 2002a). Water resources systems engineering here plays a role and is defined as '*the art and science of formulating and evaluating alternative water management plans and selecting that particular set of actions that will best accomplish specified objectives, within the constraints of governing natural laws, engineering principles, economics, environmental protection requirements, social and political concerns, legal restrictions, and institutional and financial capabilities.'* (Wurbs & James, 2002b)

When the systems approach is applied to water resources engineering, the general concept of the decision process defined by Duggal and Soni is as shown in Figure 5

(Duggal & Soni, 1996). It is important to note that the selection of the best fitting project may be an iteratively repeated process.

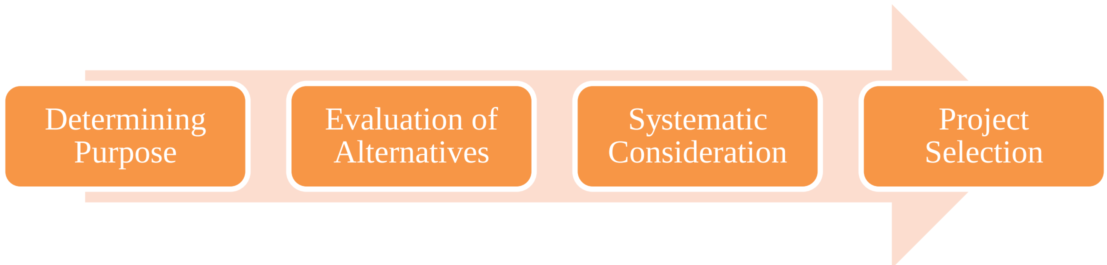

Figure 5. General Concept of Selection of Water Resources Project. (Adapted from Elements of Water Resources Engineering book (Duggal & Soni, 1996))

Wurbs and James presented pretty much same process: the general steps of the decision process are definition of problem(1), establishing objectives(2), formulating feasible alternatives(3), evaluating the alternatives(4), and selection the best alternative(5) (Wurbs & James, 2002b). Likewise, these steps conceptually match US Federal methodology of '*US Proposed National Objectives, Principles and Standards for Water and Related Resources Implementation Studies*' (Council on Environmental Quality (U.S.) Executive Office of the President, 2009). Federal planning process are as seen in Table 4:

1. Identify the study objectives and ensure that Federal participation in the study is warranted based on the likelihood of fulfilling the National Water Resources Planning Objectives;
2. Identify and assess the water and related resources problems, needs, and opportunities relevant to the planning setting associated with the study objectives;
3. Inventory, analyze, and determine the existing and most likely future water and related resources conditions within the study area relevant to the identified problems and opportunities;
4. Formulate alternatives, including identifying the No Action alternative, as well as nonstructural and structural alternatives, and combinations of nonstructural and/or structural measures to ensure that all reasonable solutions are considered;
5. Evaluate the potential effects of all reasonable and viable alternatives; a) Evaluate the potential effects, positive and negative, on the significant resources relative to the most likely conditions without action, and b) Evaluate and display the potential effects of alternatives in a systematic manner.
6. Compare alternatives;
7. Select and recommend the plan.

Table 4. Revised Federal Water Resources Planning Process, (Reprinted from 'US Proposed National Objectives, Principles and Standards for Water and Related Resources Implementation Studies' (Council on Environmental Quality (U.S.) Executive Office of the President, 2009)

2.3.2.2 Water Infrastructure Systems

People tend not to think about how water enters their homes, croplands, and facilities. Often a water infrastructure system interfaces seamlessly with nature: natural or constructed reservoirs, storage tanks that make water available on demand, pumping stations that extract water from aquifers, and even canals that transport the water. Treatment facilities, moreover, process raw water or wastewater for a specific end-use (Duffy, 2013). Desalination plants, recently growing infrastructure type, can be considered as water infrastructure that increases available fresh water by converting seawater and brackish water (Beltran & Koo-Oshima, 2006). Water distribution systems can be a network of open channels, covered tunnels, and pipes that convey water through wild fields, rural lands and urban areas to its ultimate end-users (Duffy, 2013).

Until the end of the last century, water management and planning focused on physical water distribution to users by state agencies. As a matter of fact, United States has built roughly 800,000 miles of freshwater pipelines, and 600,000 miles of sewer lines in addition to reservoirs, and treatment facilities (Crocker & Driscoll, 2004). As governments completed their hydraulic infrastructures, governmental water resource policies increasingly focused on managing water allocation (Kemerink, et al., 2016), first in developed countries and gradually developing countries as well.

2.3.2.3 Popular Water Management Approaches: Shift from IWRM to the Nexus

By the 1990s, not only the scientific communities but also global agency networks recognized the challenges of governing the integration between sectors utilizing limited fresh water resources and the necessity of Integrated Water Resource Management (IWRM) emerged (Mohtar & Lawford, 2016). Global Water Partnership [GWP] was founded by consensus of several national and global agencies in 1996 and dedicated to foster IWRM. IWRM is defied by GWP as *"a process which promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare without compromising the sustainability of ecosystems and the environment."* (GWP, 2010). The WEF Nexus approach can be considered relatively newer here compared to IWRM. The fundamental difference can be seen as IWRM approach aims to reconcile diverse water resource demands of multiple stakeholders, which may or may not include food and energy sectors, whereas the nexus initially focuses on interrelationships of WEF resources, and dual relationships between water, energy and food (Mohtar & Lawford, 2016).

It is worthy of note that water is relatively local resource compared to food and energy resources that are even transported cross-continental. IWRM approach plays an effective role to work on water-related activities in a basin or watershed. On the other hand, boundary of a Nexus study can be variable depending upon the focus of the study: national, regional, and even local. Also, depending upon the problem, the nexus approach is eligible to focus on a specific sector in the system rather than IWRM focusing on water resources firstly (Mohtar & Lawford, 2016). Translating science into strategic policy across multilevel governance remains ambiguous and makes clear that more local nexus approaches are essential (Benson, et al., 2015). The nexus, in fact, should be seen as a cooperation way to solve conflicts while building the issues on WEF nexus analytics.

Dialogues are considered vital for these transitions between scientific community, policy makers, the supply chain environments, and consumers (Mohtar & Lawford, 2016).

"The nexus approach, which is based on holistic systems theory, is needed to help identify hotspots in the nexus, since one sector does not dominate sustainability" (UNU - Flores, 2015)

WEF nexus is considered a platform which helps build more sustainable future due to the dynamic relationships between water, energy, and food systems. In doing so, existing disciplinary behind the systems cannot be replaced. Instead, the platform should gather various WEF disciplinary pillars so that provide solutions such as increasing efficiency, not optimizing any one over another (Mohtar & Lawford, 2016). FAO describes the platform as *"a useful concept to describe and address the complex and interrelated nature of our global resource systems, on which we depend to achieve different social, economic and environmental goals"* (FAO, 2014c). From global goals as SDGs to regional, and local goals, the WEF nexus serves to balance the different interests since private sectors, public sectors, and civil societies have different perspectives on the same resources (Mohtar & Lawford, 2016). Each system has boundaries based on the perceptions, interests and constraints. The organization, analytics, tradeoffs and complex implications can be solved while limiting the system to boundaries (Morgan, 2005). Therefore, a WEF nexus study is built upon national, regional, and local boundaries, which can be considered implementation areas.

2.3.3 Multi Criteria Analysis on WEF Nexus

Aforementioned planning processes for water resources planning and management studies are widely used around the world (ICOLD, 2010). Decisions in water resources management and planning naturally influence several sectors and even other resources. Multiple Criteria Analysis (MCA) therefore has been in literature to analyze multiple objectives in water resources decision makings. The MCA techniques aims to score the options based on multiple criteria which can be measured using various units and rank them. These scores further are evaluated and ranked based on criteria. The existing MCA techniques intend to support decisions in water policy and supply planning, decision on water-related infrastructure selection, and water project appraisal (Hajkowicz & Collins, 2007). As for WEF nexus, it is a platform that initially begins from focusing the interrelations between water, energy, and food systems (Mohtar & Lawford, 2016). Furthermore, the nexus platform can address any challenges and mitigate any burden on not only water but also energy, and food resources. Therefore, the WEF nexus can provide more holistic approaches while deciding on water-related projects that can help build more sustainable future (OECD, 2014).

2.4 Texas Water Law, Management and Planning

2.4.1 Water Law in Texas

Water law in Texas has categorized the water resources of the state into three: natural surface water, diffused surface water, and groundwater. All three have their own water law system (Kaiser, 2005).

According to Texas Water Code, the surface water is described as *"The water of the ordinary flow, underflow, and tides of every flowing river, natural stream, and lake, and of every bay or arm of the Gulf of Mexico, and the storm water, floodwater, and rainwater of every river, natural stream, canyon, ravine, depression, and watershed in the state"* and owned by the state (Texas Water Code Sec. 11.021, 1977). For surface water law, both legal doctrines (the riparian and the prior-appropriation which are used in the US) are recognized in Texas. While the prior-appropriation doctrine is based on the concept of "first come / first served licensing", the riparian doctrine, as can be understood from the name, provides water use rights to the land owners that have lands adjacent to a stream (Wurbs, 1995).

Another categorized water type is diffused surface water according to Texas water law. Water such as drainage water and runoff which has not yet entered a natural watercourse is accepted water of landowners. Once the water enters a natural water course, it starts to be considered state-owned surface water. In brief, diffused water may be captured, hold and used by landowners before it enters a watercourse (Kaiser, 2014) (Dowell, 2013b).

Groundwater, water percolating below the surface of the earth crust (Texas Water Code Sec. 35.002., 2015), is considered private property (Kaiser, 2005). English common law which have been followed by the state of Texas with regard to groundwater laws provides absolute ownership for groundwater (Wurbs, 1995) (Kaiser, 2014). Unlike surface water resources, landowners are able to own, use, and in fact sale water captured in their own land (Wurbs, 1995). In some cases, conflicts happened in groundwater withdrawing as some users claimed their groundwater had been pumped out by other adjacent users. The Rule of Capture also has been followed in Texas since 1904 to determine who owns the groundwater in Texas after (Kaiser, 2005). This rule basically allows landowners to pump water as much as they wish regardless of the depletion due to water withdrawing. As a result of which, Texas groundwater law is referred by many as "law of the biggest pump" (Dowell, 2013a) (Wurbs, 1995).

However, it is important to note that Texas water law have various exceptions in both surface and groundwater sources. Those exceptions were emerged and legalized after some experienced cases, conflicts and court decisions (Kaiser, 2005) (Dowell, 2013a).

2.4.2 Water Management in Texas

Texas state water programs are administrated by several agencies. Milestones of water management are collaborations and consensus in the second largest state of U.S. TWDB and Texas Commission on Environmental Quality (TCEQ) comes forefront with regard to taking responsibility for water related issues. The TWDB is in charge of statewide planning, financial assistance for water related projects and development of water conversation. TCEQ is mainly on the side of administrating natural resources and the relationship of them with human health. TCEQ administration covers also water right issuance. Another agency playing a key role in the activities of TWDB and TCEQ is Texas Park and Wildlife Department (TPWD) from the points of preserving and development of wildlife and ecosystems. (Wurbs, 2015).

Several River Authorities in Texas are responsible to develop and protect water resources of the state at regional and basin levels (Harper & Griffin, 1988). Existing 99 groundwater conversation districts are working for developing convenient use of groundwater resources and implementing management plans (TWDB, 2016d). When it comes to water supply infrastructures, they are constructed, maintained, and operated by cities, irrigation districts, river authorities, municipal water districts and private water utilities (Wurbs, 2015).

2.4.3 Texas Water Planning

The TWDB describes preparations of state-wide water plans as its own central mission (TWDB, 2016h). Although the first plan had been published in 1961, it was updated 3 times until 1990. After new amendments to the Texas Constitution added in 1997, TWDB began to develop 16 regional plans and one combination of all as state-wide water plan which forecasts upcoming 50-year at each 5-year planning cycle. (Wurbs, 2015). These 16 regional water plans guide water consumers including municipal, industrial and agricultural communities and recommend policy and legislative alterations. Besides, TWDB quantifies, evaluates, and projects current and decennial years of upcoming 50-year with regard to water supplies and needs. The most recent state water plan, the 2017 state water plan (TWDB-2017), was adopted in May 2016 (TWDB, 2016a).

TWDB-2017 is publicly available at TWDB website and contains extensive information regarding current and future water issues of Texas. In this sense, future populations, water demands, supplies, needs, management strategies and financing needs are discussed widely. The population of Texas, with the fastest population growth rate of the nation, is expected to increase from 29.5 million to 51 million from 2020 to 2070, which is roughly 70% rise in 50 years. Despite anticipated sharp rise in the population, annual state-wide water demand is projected to increase by only 17% thanks to water management strategies. Main water use conservation is planned to be in agricultural water use in the state of Texas (TWDB, 2016a). Figure 6 summarizes anticipated water use by sectors and population growth.

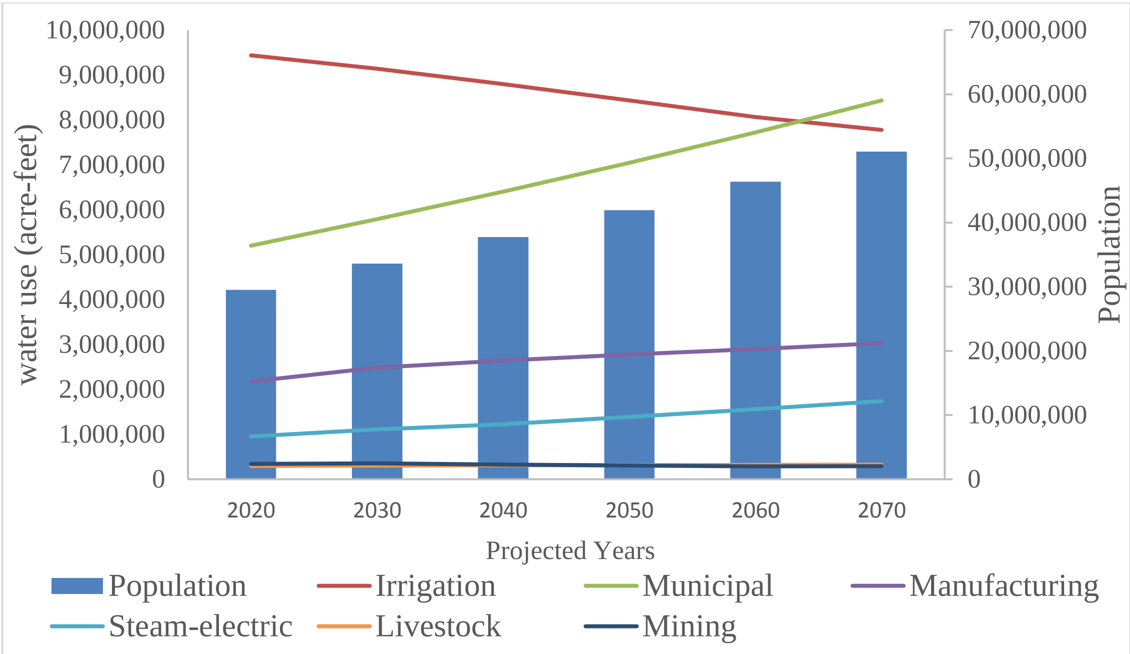

Figure 6. Projected Water Demand by Use Sectors and Population (Adapted from TWDB-2017 (TWDB, 2016a))

2.5 Matagorda County Profile

2.5.1 Background and Boundaries

Matagorda County of Texas is located on south-west of city of Houston and nearly the middle of Gulf Coast, see Figure 7. The county covers 1,613 square miles land of the Texas Gulf Coastal plain and wetlands (Kleiner, 2010). Matagorda County is surrounded by Wharton County to the north, Brazoria County to the east, and Jackson County and Calhoun County to the west [see Figure 8]. The Gulf of Mexico border with Matagorda County consists of Tres Palacios and Matagorda Bay on the western half of the county and East Matagorda Bay on the eastern half, all sheltered from the Gulf by the Matagorda Peninsula (TWRI, 2017).

Figure 7. Location of Matagorda County (Data Source for Shapefiles: TNRIS (TNRIS, 2015a))

The name of the county, Matagorda is originally a Spanish word and refers to the term of "thick bush". The county was named by Spanish colonists of the region in the 16^{th} century. (Kleiner, 2010). According to the 2010 Census, 36,702 people live in the county. Currently, it is estimated that the number of people be around 36,598 (US Census Bureau, 2015). The population of Matagorda has showed slightly downward trend in the recent a few decades with some fluctuations. Texas Demographic Center, however, expects that the county's population will increase again in the upcoming decades (Texas Demographic Center, 2016a). Major cities of the county are Bay City and Palacios. The main sectors which employ the majority of people are agriculture, energy production, and chemical industry (MCEDC, 2016). Figure 8 presents cities of Matagorda as seen below.

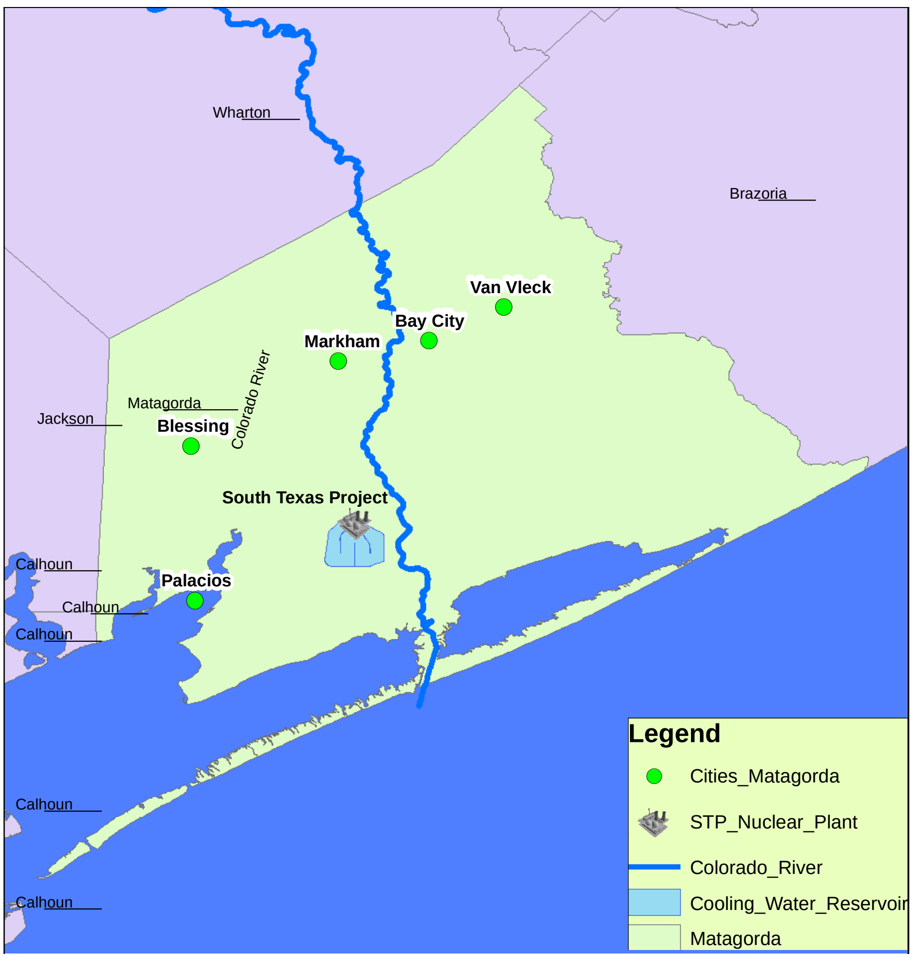

Figure 8. Matagorda County Cities (Data Sources for shapefiles: TNRIS, TWDB (TWDB, 2009) (TWDB, 2014))

Matagorda County is located in Upper Cost climate division, one of the 10 divisions of the state of Texas. The climate data of Upper Coast from 1970 to 2016 indicates that the year of 2011 was the driest year whereas 1973 was the wettest (NOAA, 2016). The Figure 9 illustrates historical annual precipitation and the recent drought can be seen in Bay City, Matagorda.

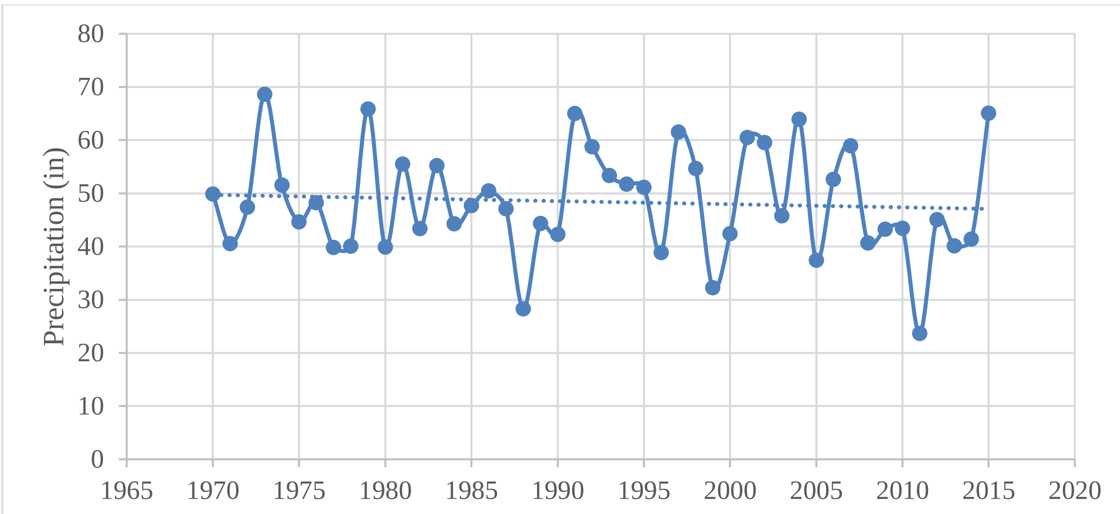

Figure 9. Historical Annual Precipitation in Matagorda (Data Source: NOAA's NCDC)

The Figure 10 below shows historic extreme year in terms of weather.

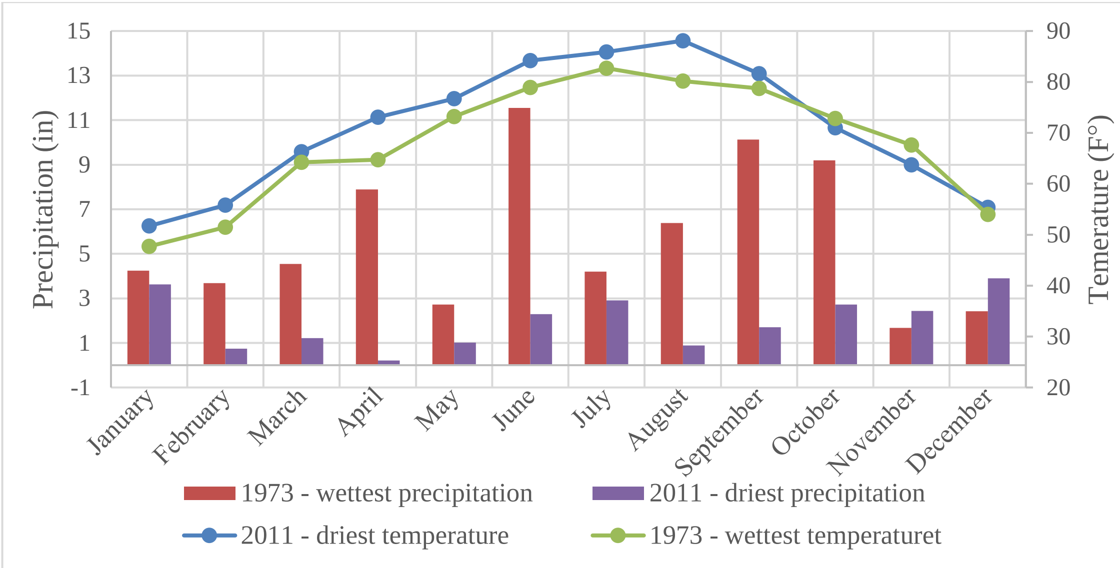

Figure 10. Historic Wettest and Driest Years (Data source: NOAA's NCDC)

While the annual precipitation is around 48 inches averagely per year in Matagorda, the county received less than 24 inches in 2011. The closer views of historic precipitation which plays an immense role for agricultural sector are shown as Figure 11Figure 12 below.

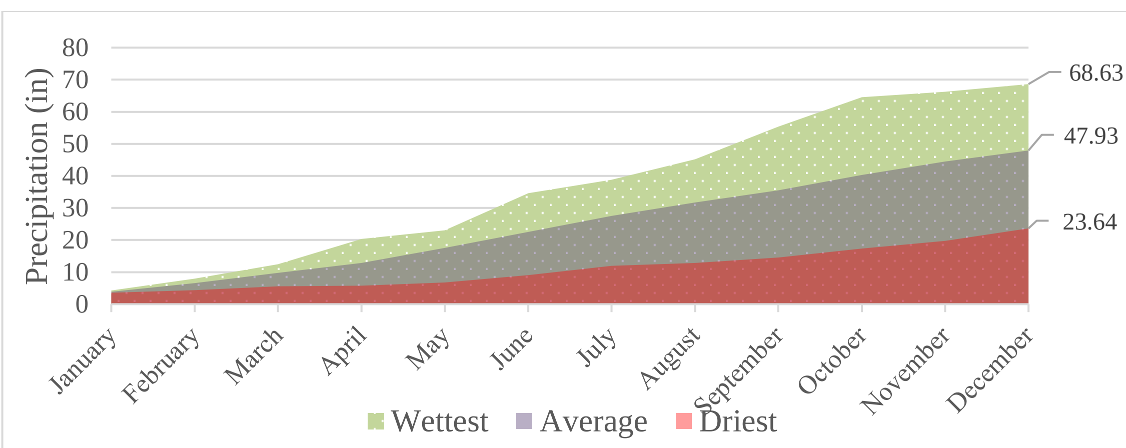

Figure 11. Historic Cumulative Precipitations of Extreme Years (Data source: NOAA's NCDC)

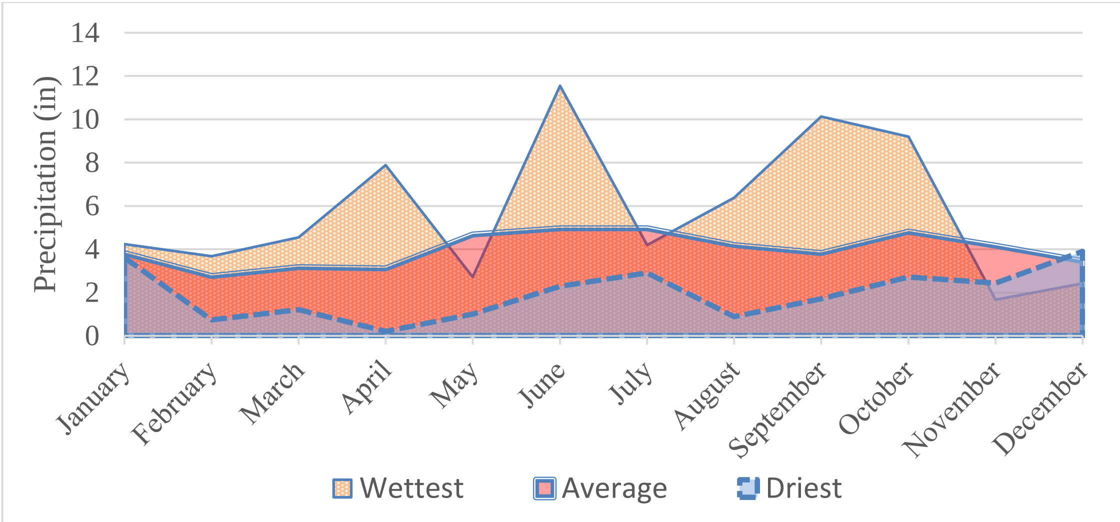

Figure 12. Historic Monthly Precipitation of Extreme Years (Data source: NOAA's NCDC)

2.6 WEF Nexus in Matagorda

Water, energy, and food portfolios and their trends and background will play a key role while building a WEF nexus model. Each of the primary resources are analyzed individually here to build a background which help figure out tradeoffs. Only through analyzing the WEF nexus in Matagorda from various angles can we arrive at a warranted conclusion.

2.6.1 Water Portfolio and Issues

2.6.1.1 Matagorda: One of the Most Water Stressed Counties

TWDB's plans provide unique information regarding water stressed regions in the state. As far as 2012 Texas Water Plan (TWDB, 2012) is concerned, (that plan was the most recent state water plan when this study began), two major regions come forefront in terms of water stress: the high plains and the gulf coast. Those regions are expected to have water scarcity in the future although some of the future water management strategies to mitigate the scarcity were taken into account. In Texas, while water rights are issued, municipal and industrial water use have higher priority than agricultural water use (TCEQ , 2015). When ranking the regions in terms of water scarcity, agricultural water need of each county better reflects the level of water scarcity.

The most water stressed areas are found in north-west Texas, known also as high plains, where irrigation is mainly supplied by Ogallala Aquifer. The excessive water use during the recent 50 years caused the decline in water levels and was concluded environmental and economic problems (Bowman, 1990). Furthermore, the farmers at high plains have been switching their irrigated farms to dryland farms since the only available water resource, Ogallala Aquifer, have become unreasonable to use (Parker, 2016).

The following water stressed area as indicated in the TWDB-2012 is the middle Gulf Coastal Counties which includes Matagorda County. The land use map as seen in Figure 13 below provides an overview of the land use of the regio (Homer, et al., 2015) n. As seen clearly, most of the land is allocated for agricultural purposes, either cultivated crops or pastureland.

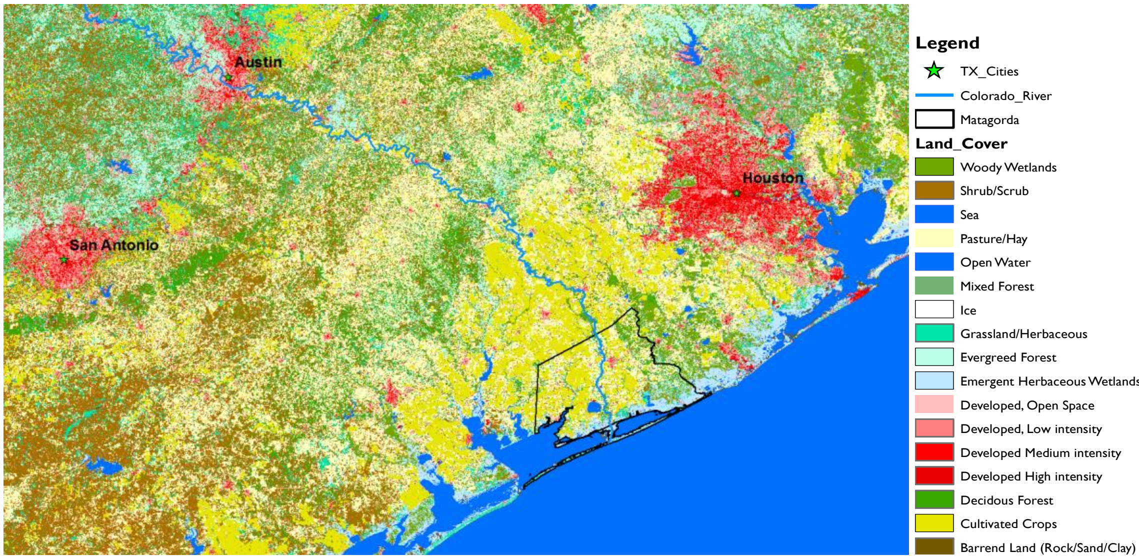

Figure 13. Land Use in the Region (Data Sources: MRLC (Homer, et al., 2015), TWDB (TWDB, 2009), and TNRIS (TNRIS, 2015a))

2.6.1.2 Matagorda County Water Issues

Admittedly, the annual average precipitation is relatively abundant here compared to most of the Texas counties, with approximately 48 inches (NOAA, 2016). Also, Colorado River, the second longest and sixth largest river by annual average flow in Texas, passes in the middle of the county (TWDB, 2016c). Last but not least, the shallow Gulf Coast Aquifer, the major aquifer paralleling the Gulf of Mexico coast is available in for water users (TWDB, 2016e). Consequently, Matagorda County has various water resources, so the variety may increase possible solutions to the scarcity when better management strategies are applied.

Agricultural water use in Matagorda County is the major water consumption among water use categories. Along with over 600 ranches and more than one thousand farms are run in Matagorda (Batchelor, 2016). The county was famous for its rice farms that inevitably consume high amount of water. The 2010-2014 drought and growing metropoles surrounding the county, however, influenced the crop types dramatically. The recent USDA's census, 2012, indicates that Matagorda County is ranked 24th among 254 counties for market value of crops sold not including livestock, poultry and their products. Besides, more than half of the arable land is utilized as pastureland (USDA - Census of Agriculture, 2012).

Along with agriculture, industry is one of the main players in the economy of the county. The by far largest industrial company is a nuclear plant which is one of two Texas nuclear plants. The details of nuclear plant are mentioned in the following chapters exclusively. The demands on water resources from both agricultural sector and the nuclear plant makes Matagorda County unique to study a WEF nexus approach. Moreover, among 254 counties, the county is expected to demand highest amount of water for steam electric power production is Matagorda in 2020, with 105,000 ac-ft (TWDB, 2016a). This tremendous amount of water, accounted one-third of total water resources of the county, is directly consumed by the plant for cooling. The Figure 14 illustrates water demands of electricity production by counties in Texas and Matagorda county has the largest consumption in this regard (TWDB, 2016a).

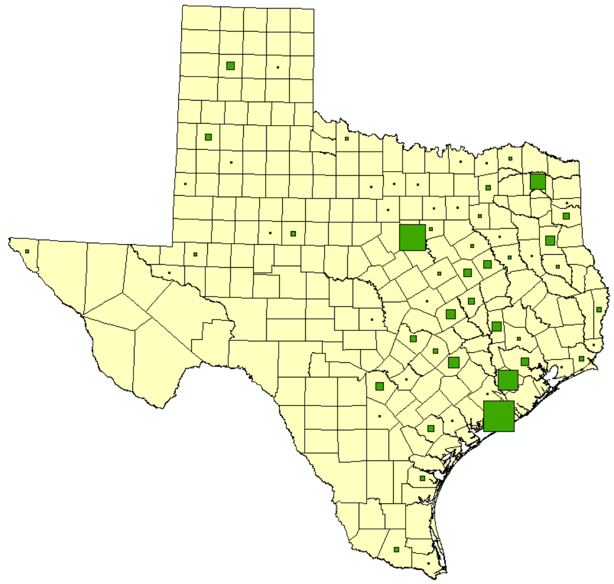

Figure 14. Water Demand by Counties for Steam-Electric Production in 2020 by Counties in Texas (Data Source: TWDB-2017 (TWDB, 2016a), Shapefile: TNRIS (TNRIS, 2015a))

2.6.1.3 Matagorda Water Resources and Their Availabilities

There are currently two water sources to supply water needs in Matagorda County: The Colorado River and the Gulf Coast Aquifer. Even though the county does not have a large population and receive relatively abundant rainfall, the limited available water of the resources makes Matagorda County one of the most water-stressed counties in the state. The recent 2010-2014 drought demonstrates that current water use practices and water allocations are neither sufficient nor sustainable.

Surface Water

For surface water resources, Texas is one of the states combining riparian rights and prior appropriation water rights doctrines. In conjunction with rising public awareness and environmental threats, obtaining new water rights has become more difficult after

Senate Bill 3 legislated in 2007. According to Matagorda water rights issued by the TCEQ, the existing water rights for Matagorda County mainly belong to two sectors: agriculture and industry (TCEQ, 2016) [see appendices]. Water rights issued for other sectors such as municipalities and mining companies can be negligible in Matagorda County due to either very low diversion amounts or inactivation. Among irrigation water rights, the Lower Colorado River Authority (LCRA) comes forefront for having more than 262,500 acre-feet permitted water right annually. In addition, LCRA also has the highest priority among other irrigators. In non-drought years, most of the farmers in Matagorda County used to buy irrigation water from LCRA to supply their farms, mainly rice farms. However, the recent drought and growing cities (Austin and some central Texas cities) on the upstream of Colorado River resulted changes in water use trends. For instance, LCRA chose to not supply water to the downstream irrigation districts including Gulf Coast irrigation district. That cutting off water for rice farmers was the first time in LCRA history since 1934 (Henry & Barer, 2013). The annual averaged flow of Colorado river near to Bay city [at USGS gauge Station ID 08162506] can be seen in Figure 15 derived using HEC-DSS 2.0.1 (USGS, 2016a).

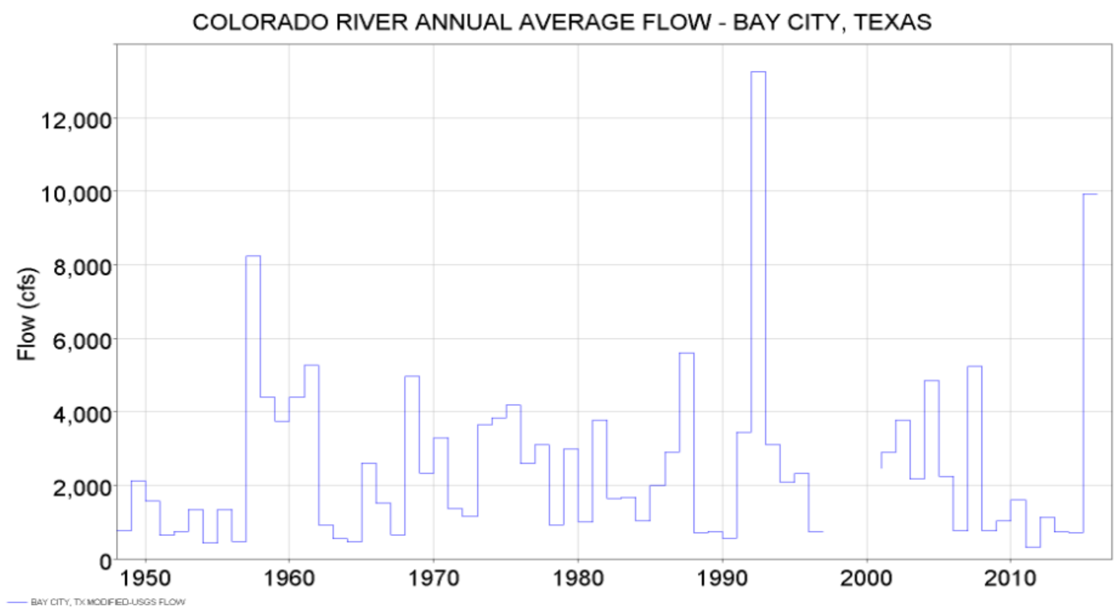

Figure 15. Annual Average Flow of Colorado River (Gauged nearby Bay City USGS' station ID is 08162506 (USGS, 2016a), derived using HEC-DSS 2.0.1)

The Colorado River provides tremendous amount of irrigation via Gulf Coast Irrigation District conveyance system canals. Some part of the canals exists in Wharton County on upstream.

In addition to the water rights of the LCRA, some irrigators carry their own rights individually. They have totally 38,096 acre-feet of permitted water use. Surface water irrigation in the region relies mostly on the conveyance, which has many maintenance issues. The conveyance canal distribution system was built in 1920s. Seepages and other type of water losses significantly reduce the efficiency of the canals. In these conditions, it is reported that farmers will only allocate water from the river with approximately 30% of water loss (Bonaiti & Fipps, 2013). Overall, it can be stated that the Colorado River with current irrigation canals and irrigation practices is an insufficient source for agricultural water needs in Matagorda County, especially during drought conditions which is expected to happen in the future more frequently.

South Texas Project Nuclear Operation Company (STPNOC) is the largest non-agricultural consumer in the county, with 120,000 acre-feet permitted annually (TCEQ, 2016). Due to the critical need for water at the South Texas Project (STP) nuclear plant, it is declared that water will be allocated to the plant even in extreme drought conditions. Moreover, STP will be able to get 20% more of total water-rights in case of emergency which have never occurred (USNCR , 2011). Lastly, there are also some industrial companies holding surface water rights which can be considered relatively less [see appendices] (TCEQ, 2016). They will be discussed in the following chapters.

Groundwater

As seen in Figure 16 below, the only feasible and used fresh groundwater source for Matagorda County is the Gulf Coast Aquifer, the second largest aquifer in Texas. However, the depletion in the aquifer has drawn down water levels, dropped as much as 350 feet in some parts on the aquifer. This has brought concern to those responsible of managing the groundwater, who have in turn warned stakeholders and the people of Texas to use the resource efficiently (TWDB, 2016e).

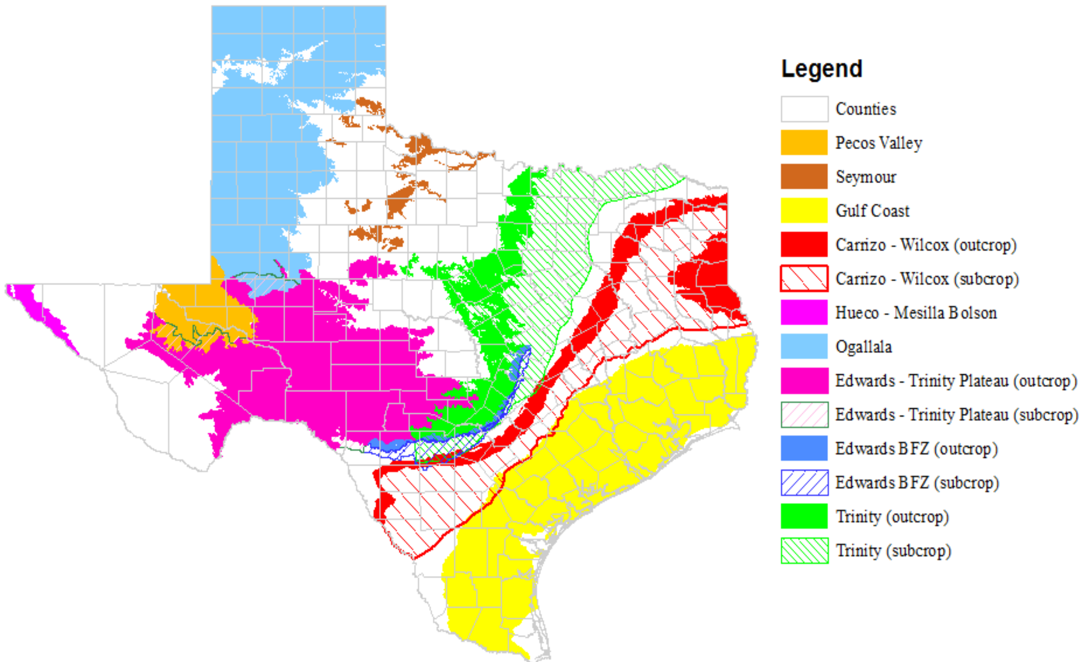

Figure 16. Groundwaters of Texas and Matagorda County (Shapefile Source: TWDB (TWDB, 2006) - Major Aquifers and TNRIS (TNRIS, 2015a))

Availability of groundwater resources must be evaluated different from the availability of surface water since Gulf Coast Aquifer is not limited to the boundaries of Matagorda County. For managements and regulations of groundwater use of the Matagorda County, it belongs to TWDB Groundwater Management Area 15 and the Coastal Plains Groundwater Conservation District. The TWDB reports state that from 2010 to 2060, available and recommended groundwater withdraw value for Matagorda County is 45,896 acre-feet of non-brackish groundwater (TWDB, 2015).

2.6.2 Energy Portfolio

Matagorda County is a rural and coastal county having diverse industry. One of the two Texas nuclear plants, chemical companies, oil & gas storages, manufacturing, and pipelines are located in the county (MCEDC, 2016). Those industrial companies play significant roles for utilizing and producing water and energy resources. From energy production processing perspectives, Matagorda has quite diverse energy resources and producers (EIA, 2016d). The Figure 17 illustrate the locations of major energy industry.

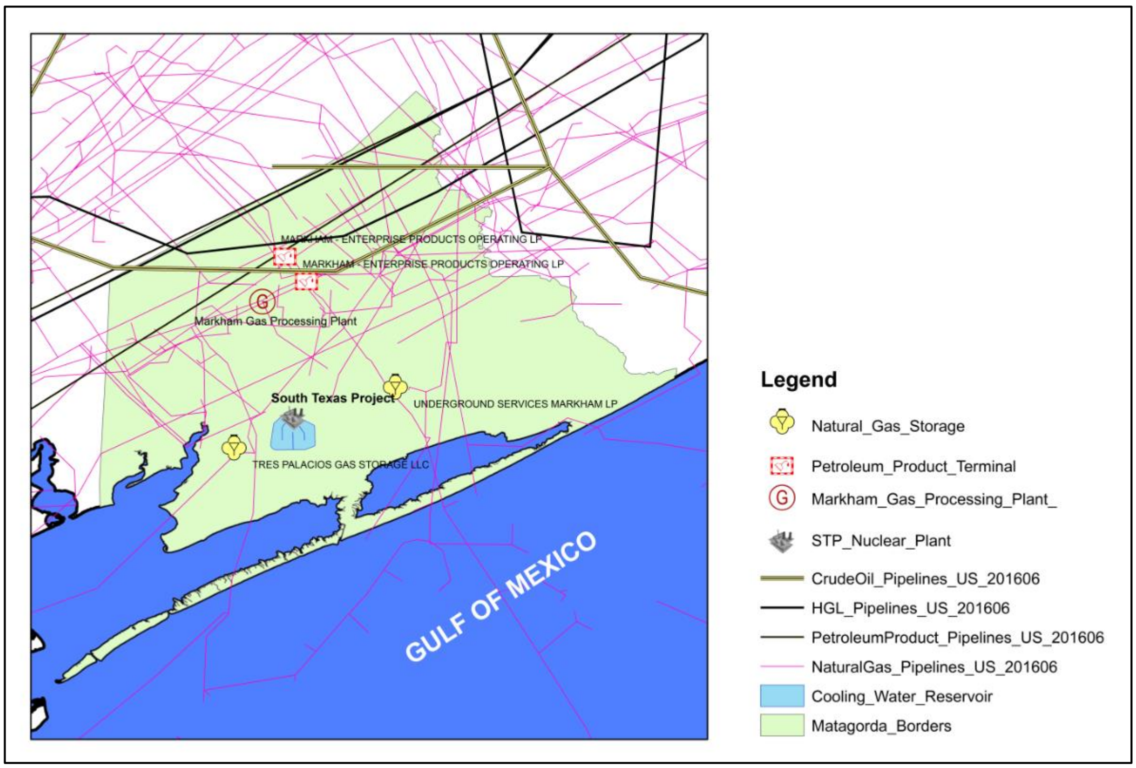

Figure 17. Matagorda County Energy Industry, not Including Oil & Gas Wells (Data Shapefiles: EIA (EIA, 2016b) and TNRIS (TNRIS, 2015a))

2.6.2.1 Oil and Gas Production

Unlike water and agriculture sectors, most of oil & gas data is not publicly available for Matagorda County. Nevertheless, partial useful information can be found regarding annual oil production, drilling permits and gas production. Near to Matagorda County, several offshore oil & gas platforms have been established and some of them are considered being in federal waters while others are considered in the border of Matagorda (EIA, 2016d). When the official boundary of the county considered, the production rates show downward trend from 2008 to 2016 with some negligible fluctuations (RRC Texas, 2016).

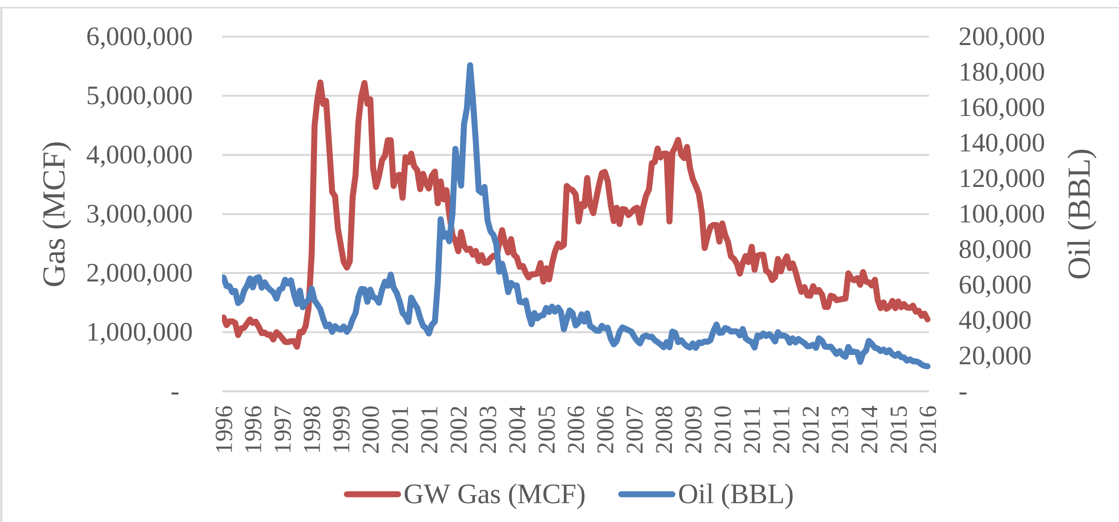

Figure 18. Historic Monthly Oil & Gas Production in Matagorda (Data for the chart from Rail Road Commission of Texas (RRC Texas, 2016))

Water and oil & gas nexus has no a straightforward relationship that can be seen in Figure 18. Water produced during the production of fossil-fuel production is named produced water (Engle, et al., 2014). The amount and quality of produced water varies widely in different places (AGI, 2016). The varieties depend upon type of energy produced, production process, hydrological, and geological conditions of the field and the region (Healy, et al., 2015). Some contaminants in the produced water can reduce the quality of water resources significantly. As an illustration, some of the municipal water treatment plants in Pennsylvania, have been utterly overwhelmed. After several conflicts and environmental considerations, the state started to require some operators to treat their produced water before turning it back to nature. The typical municipal wastewater treatment plants have not been established for treating water resources as polluted and salty as the produced water (Schimidt, 2013) (Healy, et al., 2015).

2.6.2.2 Nuclear Energy Production Background

South Texas Project (STP) is the single largest water consumer in Matagorda County. The nuclear plant is one of two power plants in the state of Texas along with Comanche Peak Nuclear Power Plant near Glen Rose. The power plant is owned by a consortium named South Texas Project Nuclear Operation Company (STPNOC), which consists of Austin Energy (16%), CPS Energy (40%) and NRG Energy, Inc. (44%) (STPNOC, 2016). STP nuclear plant provides electric power to near counties and large Texas cities: Houston, Austin, and San Antonio (see Figure 7). The plant provides jobs for around 1,200 employees and it makes STPNOC the largest employer and source of revenue in Matagorda County (STPNOC, 2013).

Figure 19, below, shows an aerial view photograph of the South Texas Project looking south. The reactor units are marked with arrows and the labels for Unit 1 and Unit 2. South of the reactor units is the 7,000-acre man-made cooling reservoir enclosed by a large ring-dike. The cooling water reservoir at STP named Main Cooling Reservoir (MCR) has a volume capacity of 202,988 acre-feet during normal operations (Wurbs & Zhang, 2014). The dimensions of MRC are approximately 12 square miles at 29 feet deep. The Colorado River can be seen on the left side of the figure. A pump intake station was built on the banks of the Colorado River just out of the picture near the "Makeup from river" label to refill the cooling reservoir from losses due to evaporation or seepage. In the distance is West Matagorda Bay sheltered from the Gulf of Mexico by the Matagorda Peninsula.

Figure 19. South Texas Project (Shapefiles: TNRIS (TNRIS, 2015b), TWDB (TWDB, 2009))

2.6.3 Food Portfolio

The land use of Matagorda County indicates that most of the land in the county is allocated for agricultural purposes [see Figure 13]. In this section, food portfolio is processed while looking at crop production and livestock existing in the county.

2.6.3.1 Crops

As a rural and coastal county which surrounded by metropolises of Texas to some extent, Matagorda County has a rich history with respect to agricultural industry and commerce. Rice farming was the main driver of agricultural commerce in not only Matagorda County but also Jackson, Wharton and Colorado Counties for more than 100 years. However, recent drought played a significant role to alter the agricultural pattern to diversification of crops (MCEDC, 2016). Farmers in Matagorda grow also large quantities of sorghum, cotton, soybeans, and corn (MCEDC, 2016).

According to 2012 Census of Agriculture published by USDA [the recent available census of agriculture], annual total value of agricultural products sold is approximately 130 million dollars. Around 41% of the annual sales value are from livestock, poultry and their products which are grown over 600 ranches. As an illustration, allocation of farmlands in 2012 can be seen in Figure 20. The census also reports that more than 60.2% of the land in farms are used as pastureland whereas the cropland accounted 31.2% (USDA - Census of Agriculture, 2012). When compared to the previous census published in 2007, the pastureland 9% of land were transformed into pastureland from cropland (USDA -

Census of Agriculture, 2007). The decrease in the availability of water resources played a key role for this transformation.

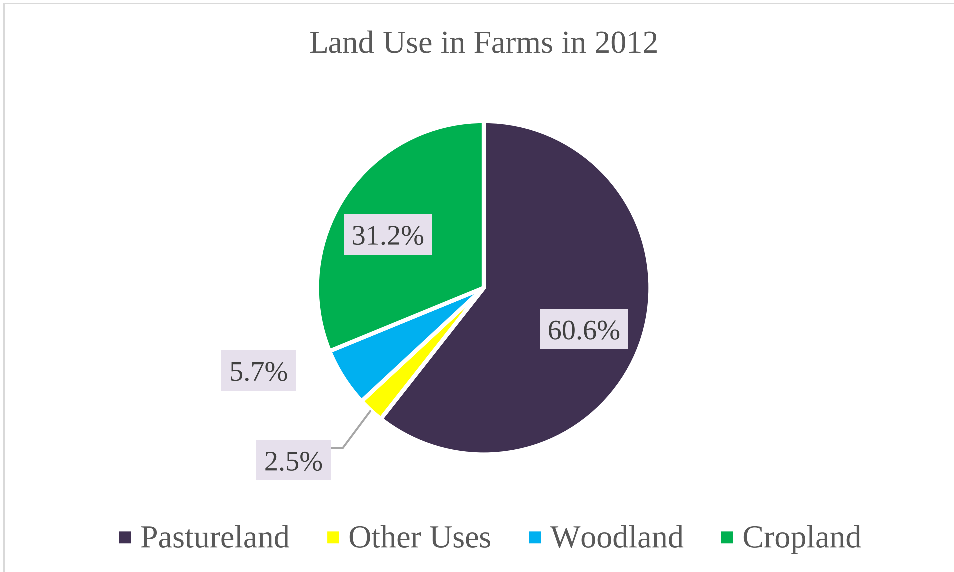

Figure 20. Farmlands Allocation in Matagorda in 2012 (Reprinted from: USDA 2012 Census of Agriculture (USDA - Census of Agriculture, 2012))

2.6.3.2 Livestock and Aquaculture

Beef production among livestock sector comes forefront in Matagorda County with approximately 40 percent of total agricultural product sales. The other livestock productions are negligible in the county. Matagorda County had 52,283 head of cattle, which makes Matagorda an essential player for beef production in Texas in 2012 (USDA - Census of Agriculture, 2012). Referencing the historical facts of Matagorda from USDA, the number of cattle have increased gradually with some fluctuations (USDA - NASS, 2016a). Beef production and sales are expected to grow and continue to have a significant role in the economy of county (MCEDC, 2016). Aquaculture is another powerful sector in Matagorda County. In fact, Matagorda has been ranked first in this area among 254 counties (USDA - Census of Agriculture, 2012).

2.7 Modules of WEF Systems

Module is defined in this study as the components and drivers of water, energy, and food systems, which can be a whole sector, industry, a governmental organization depending upon the study area. In Matagorda County, there modules were determined as drivers of the primary resources: Agriculture (1), Municipality and Industry (2), Nuclear Generation (3). Their tradeoffs show that they use and utilize pretty much whole water, energy and food in the county.

2.7.1 Agriculture

2.7.1.1 Crop Pattern

As a rural county, most of the land of Matagorda is devoted to Agriculture including livestock [see Figure 13]. The exact values for agricultural consumption is presented in Table 5. Agriculture censuses of USDA indicate that around 80% of total land has been for Agriculture, mostly pastureland. Total area of the county is 704,176 acres (USDA - NASS, 2016a).

Year	Land in Farms (acres)	Agricultural Land Ratio
2012	568,055	80.7%
2007	577,594	82.0%
2002	619,142	87.9%
1997	550,642	78.2%
1992	562,612	79.9%
1987	578,993	82.2%

Table 5. Historic Values for Land in Farms in Matagorda (Data Source: USDA Agriculture Censuses)

The cropland in agricultural land has been declining for decades although total agricultural land remains pretty much stable as can be seen in Figure 21.

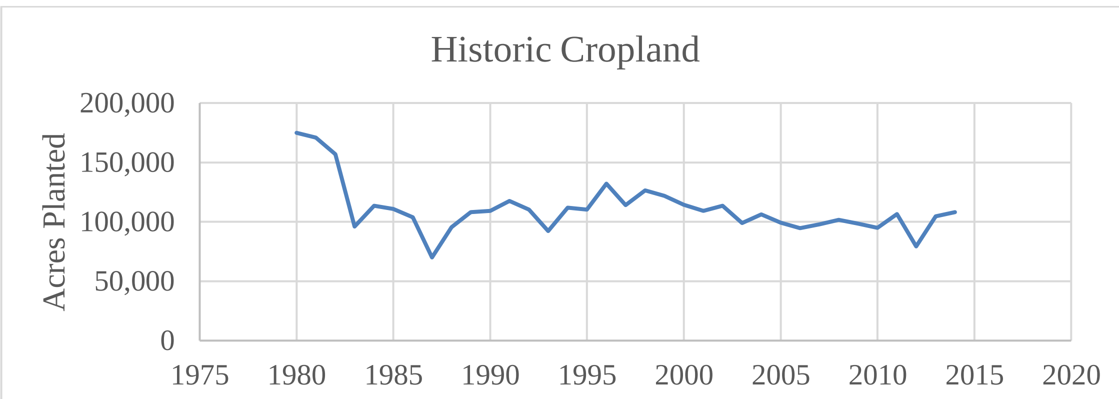

Figure 21. Historic Total Planted Areas as Cropland (Data Source: USDA Agriculture Surveys)

Referencing the Census and Surveys published by the USDA, it can be said that five major crops are dominating the county. Although a few new different types of crops have been grown in the recent years in Matagorda County, it is clear from agricultural pattern in 2014 as seen in Figure 22 that corn, cotton, rice, sorghum, and soybeans will continue to be major crops in the coastal county (USDA - NASS, 2016a).

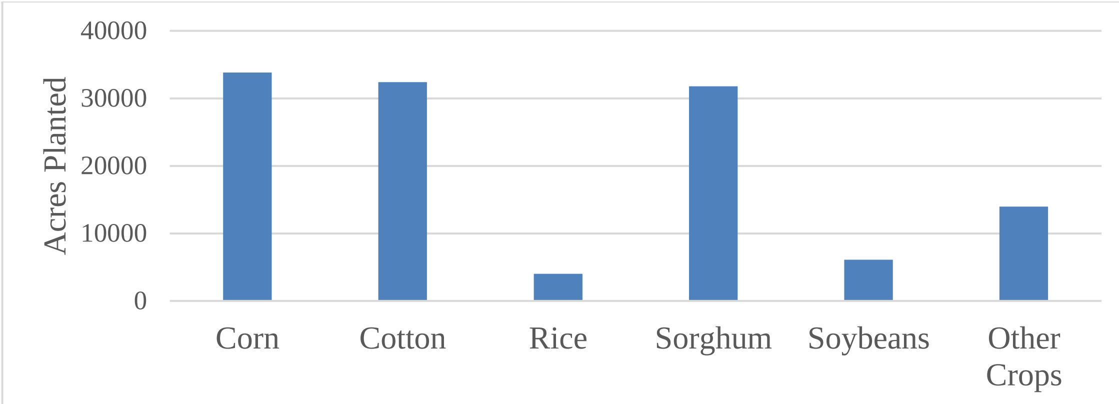

Figure 22. Agricultural Pattern in 2014 (Other Crops mostly consists of hay) (Data Source: USDA Agriculture Survey in 2014)

Although the crop types remain same, the pattern has changed occasionally because of several reasons including drought, market prices, infrastructure and transportation improvements and so on. The Figure 23Figure 24Figure 25Figure 26Figure 27 below illustrate the changes in planted areas of corn, cotton, rice, sorghum, and soybeans annually from 1980 to 2014 (USDA - NASS, 2016a).

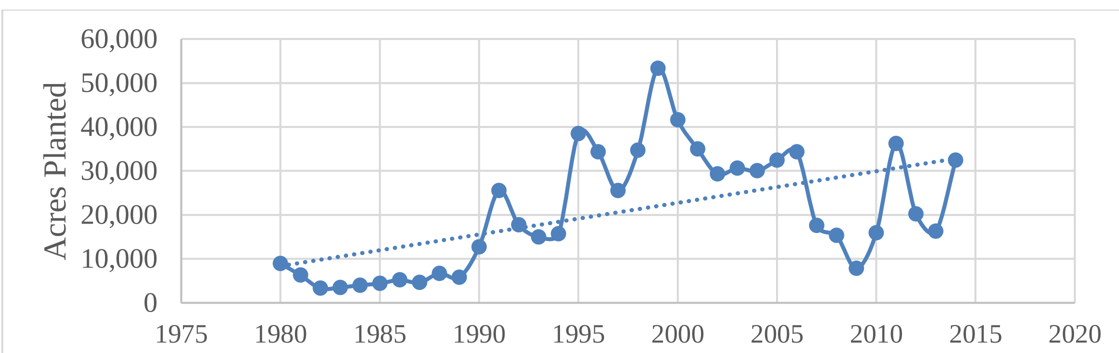

Figure 23. Historic Matagorda County Acres of Cotton Planted (Source: USDA Surveys)

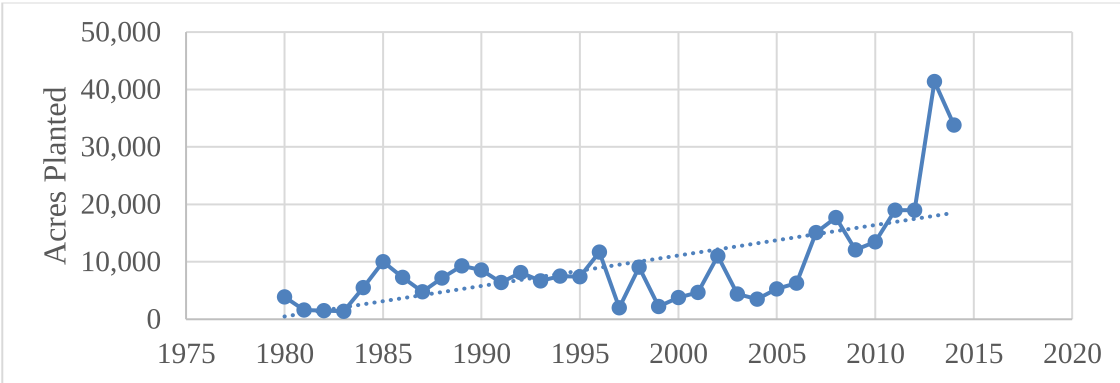

Figure 24. Historic Matagorda County Acres of Corn Planted (Source: USDA Surveys)

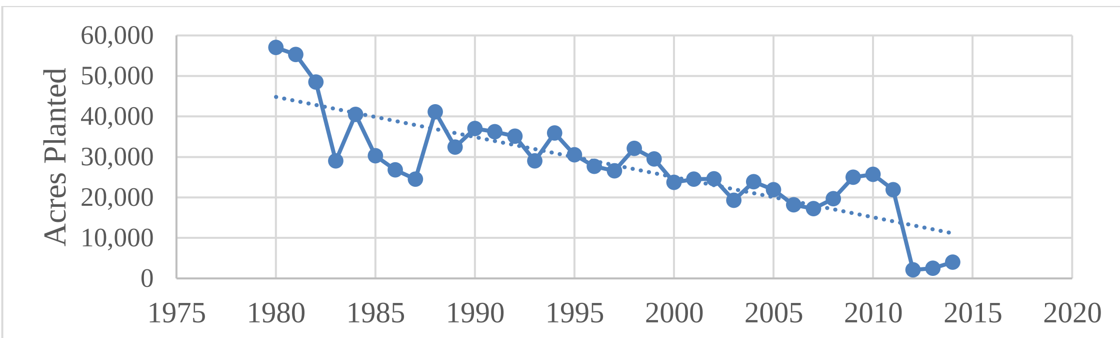

Figure 25. Historic Matagorda County Acres of Rice Planted (Source: USDA Surveys)

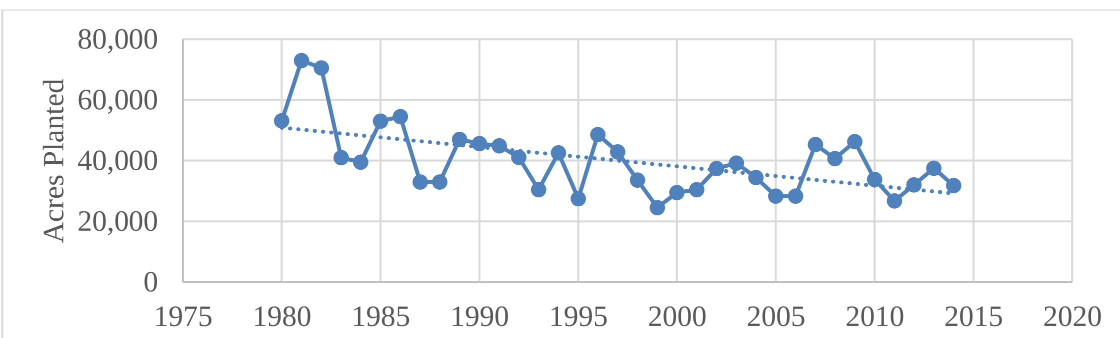

Figure 26. Historic Matagorda County Acres of Sorghum Planted (Source: USDA Surveys)

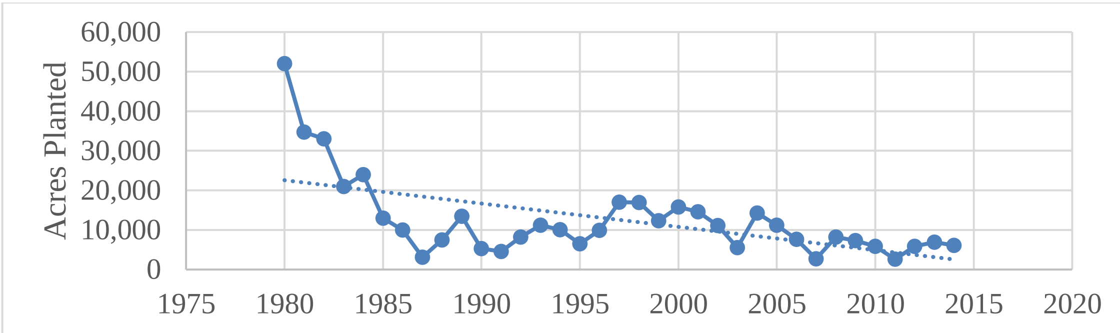

Figure 27. Historic Matagorda County Acres of Soybeans Planted (Source: USDA Surveys)

As clearly seen from the trendlines (dashed lines) of the charts above, cotton and corn planting have showed an upward trend while rice, sorghum and soybeans planting have decreased.

2.7.1.2. Livestock

The major animal grown and sold for food sector is cattle while the others are negligible. The annual historical data since 1978 from USDA's National Agricultural Statistics Service help draw the general trend of growth of cattle (USDA - NASS, 2016a). The main purpose of livestock sector is beef and side productions of cattle. Figure 28 presents historical number of cattle in the county.

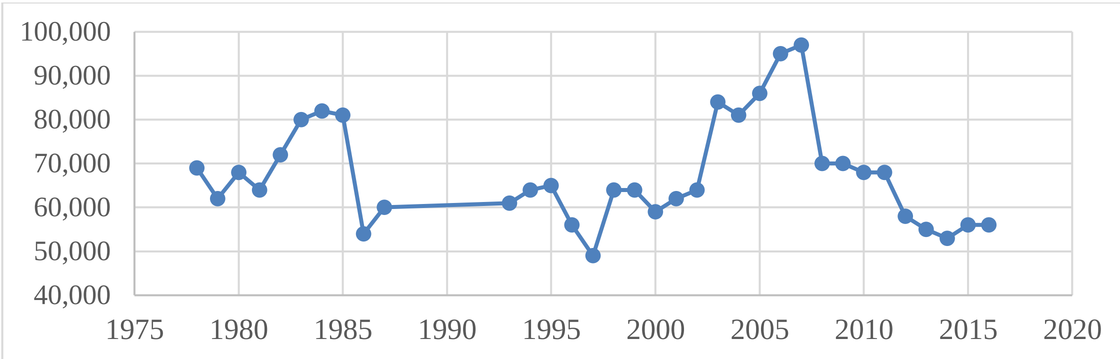

Figure 28. Historic Annual Number of Cattle Including Calves (Source: USDA-NASS)

When the number of annual cattle sold for the same period: from 1978 to 2015, approximately 50.6% of total inventory sold each year (USDA - NASS, 2016a). The market values of cattle prices have also increased in time. Figure 29 shows annual cattle prices' changes (USDA - ERS, 2016). The rise of food prices accelerates after 2000s, which is expected to continue in the future.

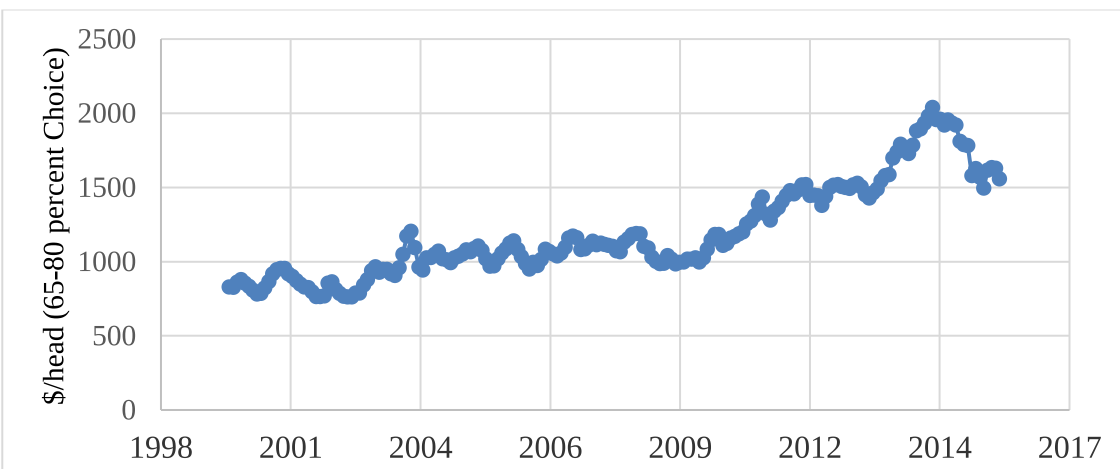

Figure 29. Historic Annual Cattle Prices (Data source: USDA – ERS)

2.7.1.3 Water Consumption and Allocations

Agricultural water use in Matagorda County is the major water consumption type among water use categories. The county was famous for its lucrative rice farms that inevitably consume high amount of water. As stated before, the 2010-2014 drought and other external factors, however, influenced the crop types dramatically in the county. Farmers in the Gulf Coast Irrigation District (most parts located in Matagorda) were forced to change their crop types to the crops that consume less water because the LCRA did not allocate water for the farmers of Matagorda County during drought periods. Still, farmers of Matagorda are expected to receive less water than its need in the next 50 years according to TWDB-2017 (TWDB, 2016a).

Farmers are currently irrigating their farming mostly via direct water diversion. In the near future, a planned new reservoir will provide water supply to agricultural lands of Matagorda County. The name of the planned reservoir is Lane City Reservoir, which is currently under construction and planned to be opened for service in 2018 (LCRA, 2015). The reservoir is planned to supply other sectors in the region even though future water allocations remains unclear.

Land owned farmers are also able to pump water from the Gulf Coast Aquifer [see Texas Water Law in Texas]. The amount of the pumped water is not currenly metered in most of the cases because of Texas water law. As most of the regions in Texas, excessive water withdrawals have caused environmental and sustainability related issues.

For the future allocations, desalination of brackish groundwater and seawater from Gulf of Mexico, city-water from Houston can be considered other options as new water resources. However, there is no planned or existed a desalination plant in the county.

2.7.1.4 Energy Consumption

Energy is needed for agricultural production due to mainly farming practices and water distribution [see Water – Energy Nexus above]. Available data and observations show that currently farming machines working with diesel are utilized for farming practices in Matagorda. Farming operations include tillage, planting, cultivation, and miscellaneous operation. Energy for water distribution is currently electricity consumption for water conveyance through pumping stations.

2.7.2 Municipalities and Industry

There are several water utilities and industries in Matagorda County which help produce, convey and utilize the WEF resources of Matagorda County. This section discusses water consumption for municipal and industrial use and their energy requirements, which play roles for the WEF tradeoffs. Water used for energy production (cooling) is evaluated individually.

2.7.2.1 Domestic and industrial Water Consumption

According to historical water use estimations revealed by TWDB, whole municipal water requirements and are supplied by fresh groundwater in the county. As for the industrial water use, water consumers have been using Colorado River and the Gulf Coast aquifer both. In 2015, for example, groundwater consumption was 1,423 acre-feet while the surface water use not including power production was 8,657 acre-feet (TWDB, 2016f).

2.7.3 Nuclear Power Generation

2.7.3.1 Energy Production Portfolio

Currently the plant is made up of two Westinghouse 4-loop pressurized water reactors with a rated electric power of 1,250 megawatts for each unit. Unit 1 became commercially operational in August 1988 and Unit 2 became commercially operational in June 1989 (STPNOC, 2013). STPNOC first tendered the application to United States Nuclear Regulatory Commission (USNCR) for the expansion of the plant from 2 reactors to 4 in 2007 (USNCR, 2016a). The process of getting licenses for Nuclear Reactor from USNCR is predictably long and exhaustive because of safety and environmental considerations. After many reviews and several reports along with corrections occurred during the nine-years period, USNCR issued Unit 3 and Unit 4 combined licenses on February 12, 2016 (USNCR, 2016b). The information of reactors are presented in the Table 6 below.

Reactor Units	Net Capacity	Gross Capacity	Construction started	Current License Expiration
Unit 1	1280 MW	1354 MW	22-Dec-75	20 August 2027 (extension pending)
Unit 2	1280 MW	1354 MW	22-Dec-75	15 December 2028 (extension pending)
Unit 3 (Planned)	1350 MW		License Issued (Sept. 2016)	40 years after construction/activati on
Unit 4 (Planned)	1350 MW		License Issued (Sept. 2016)	40 years after construction/activati on

Table 6. The General Information of Reactors of STP Nuclear Generation Plant (Source: IEAE Power Reactor Information System (IAEA, 2016) (STPNOC, 2009))

The aerial view of Figure 19. South Texas Project shows the current condition of the nuclear generation site. Similarly, the sketch of STP nuclear generation site illustrates main components of the site in Figure 30 below. It also includes proposed units.

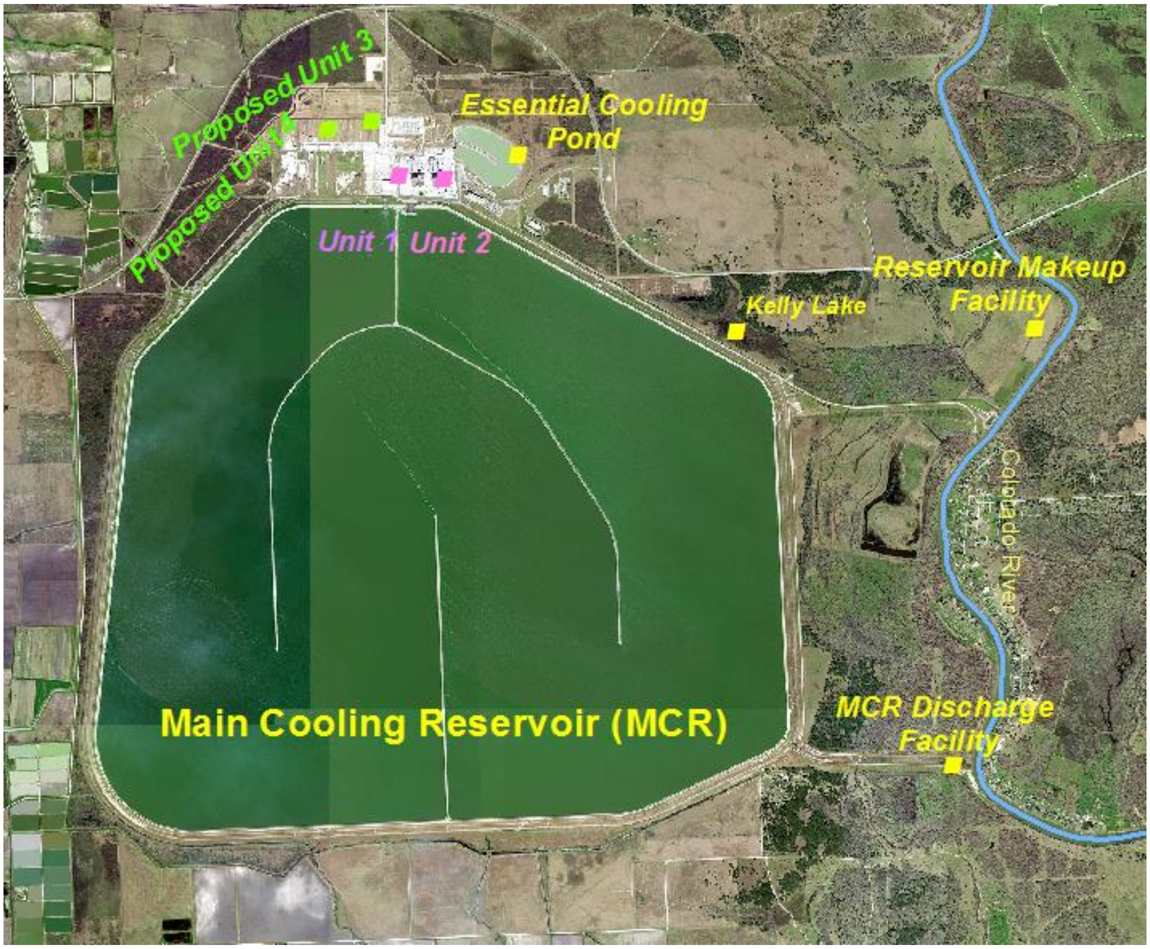

Figure 30. The Sketch of Proposed STP Site (Shapefiles: TNRIS (TNRIS, 2015b), TWDB (TWDB, 2009))

2.7.3.2 Cooling System and Existing Water Consumption

The cooling system is inevitable and essential part of nuclear plants since two-third of total produced energy is rejected as heat to the environment (USNCR , 2011). The cooling system installed for the plant is circulating water system with a pond. This pond, called MCR, is supplied with water by mainly Colorado River, precipitation, and groundwater resources and consumed due to evaporation (natural and induced because of heat), seepage, and releasing back to the river. The Figure 31 below illustrates suppliers of water cooling system and the motives of consumption.

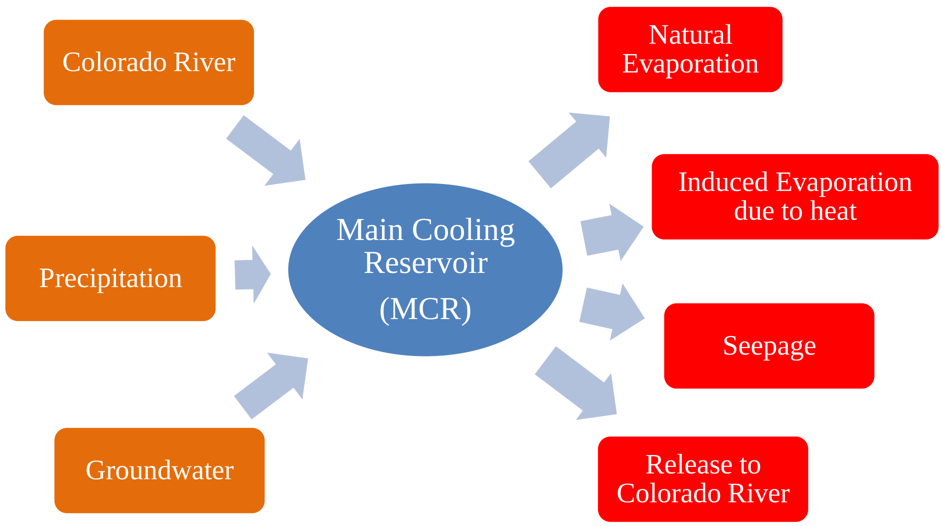

Figure 31. Schematic Overview of Water for Cooling System

MCR, which is merely cooling system of two reactors, has three water sources: precipitation, Colorado River and groundwater. STPNOC currently holds a water right for annual 102,200 acre-feet of river water, which is authorized to divert water up to a maximum rate of 1200 cfs (TCEQ , 2015). Also, a maximum of 20,000 acre-feet water can be used under special or emergent circumstances (needs special permit by LCRA). STPNOC reported in 2007 that an average of 37,084 ac-ft water was diverted from Colorado River to Main Cooling Reservoir (MCR) even though they had much more water rights (STPNOC, 2010). According to the operation permit issued by Coastal Plains Groundwater Conversation District, the limit of groundwater withdrawal is 3,000 ac-ft / year or 9,000 ac-ft / 3-year for an absolute usage (CPGCD, 2009). Annual average water withdrawal from Gulf Coast Aquifer via 5 wells located in STP site is 1,287 ac-ft from 2001 through 2006, STPNOC reported (STPNOC, 2010).

Circulating water system as main cooling system for Units 3 and 4 will dissipate 1.7 x 10^{10} Btu/hr for existing two units. Similar to units 1 and 2, the proposed Units 3 and 4 are planned to be able to use MCR (STPNOC, 2010). Water losses from MCR are seepage, evaporation, and water release to the Colorado River. Water returns Colorado River back 2 miles downstream of reservoir makeup pumping facility. New pumps are planned to be installed to support Units 3 and 4 (USNCR , 2011). The company is also planning to build two *Ultimate Heat Sink Cooling Towers* that will hold sufficient amount of water to cool the units for one month of operation following an accident. The cooling towers will receive makeup water from groundwater wells and as well as MCR. The cooling towers can be operated to provide supplemental cooling of water in the circulating system. Only Units 3 and 4 will be able to get benefit from the towers. It seems from the reports for the expansion that the primary purpose of the cooling towers is not cooling the system during normal operation since MCR is currently sufficient for 4 units and in fact more practicable and feasible. In other words, the proposed cooling towers will be actively used under problematic conditions. Lastly, beside 5 groundwater wells, STPNOC is planning to build more wells for more groundwater withdrawal (USNCR , 2011).

Evaporation inevitably occurs from MCR due to both natural evaporation and induced evaporation [because of the heat from STP Units]. By 2006, the maximum evaporation rates from MCR are reported 37,275 ac-ft and 37,200 ac-ft, respectively (STPNOC, 2008). More evaporation is likely to occur in a case as 2010-2014 drought.

Natural Evaporation is calculated using the lake evaporation data provided by TWDB. Based on the historic records, the year of 2000 is known to have the uttermost natural evaporation since 1954 (TWDB, 2016g). In 2000, in a lake located in middle of Matagorda, the magnitude of annual evaporation is 71.73 in, data indicates. Considering MCR's surface area, approximately 41,500 ac-ft evaporation from MCR was calculated.

Water is also lost due to seepage. Annual 5,700 ac-ft water enters through the Aquifer. However, 68 percent of this seepage is intercepted by the relief wells and discharged. Namely, 1850 ac-ft water goes to the aquifer (STPNOC, 2010).

2.7.3.3 Estimated Future Water Consumptions

STPNOC asserts that 74,630 ac-ft water for cooling of the 4 reactors will be consumed each year under normal conditions when all units operate (STPNOC, 2009). When the natural evaporation value of MCR is added, total annual water consumption under the most severe consumption would be 113,725 ac-ft. STPNOC holds annual 102,200 ac-ft water rights for water use of Colorado River and 3000 ac-ft from the Gulf Coast Aquifer, together 105,200 (TCEQ , 2015). Besides, the data for released water from MCR to Colorado River is missing. The release value would increase the consumption and it may play a crucial role especially under severe conditions. The below do not take the release water into account.

Current Water Resources	Average Use by 2008 (ac-ft/yr)	Limit (ac-ft/yr)
Colorado River	37,804	102,000
Groundwater	1,287	3,000
Precipitation*	27,959	13,790
Total	67,050	**118,790**

Table 7. Water Sources and Average Uses by 2008 with Limits (Data Sources: USNCR and TCEQ)

Considering the historic recorded values as seen in Table 7, total average water consumption is 67,050 ac-ft (which considers only existing 2 units). Table 8 below shows the expected water consumptions in normal and severe conditions.

Water Consumption by	Normal Conditions (ac-ft/yr)	Most Severe Conditions (ac-ft/yr)
Natural Evaporation	32,118	41,483
Induced Evaporation by Units 1&2	33,200	37,200
Induced Evaporation by Units 3&4	34,850	37,430
Seepage	1,850	1,850
Total	102,018	**117,963**

Table 8. Water Use Amounts Expected in the Future (Adapted Based on the Information in South Texas Project Units 3 and 4 Combined License Application, Part 3, Environmental Report (STPNOC, 2010))

As can be realized from the tables above, in most severe conditions, the STP plant will use 117,963 ac-ft water which is under the limit, 118,790. Nonetheless, it can be said that the plant consumes tremendous amount of water [see Figure 14. Water Demand by Counties for Steam-Electric Production in 2020 by Counties in Texas (Data Source: TWDB-2017 , Shapefile: TNRIS)].

3. METHODOLOGY

This chapter presents general concepts determined to define framework and the methods used in the study. After describing the concepts and the framework, the methods are developed based on the study objectives, which stated in Chapter 1. Here is the reminder of the objectives:

Objectives

I. Develop a systems level water – energy- food nexus platform and tool to assess tradeoffs in water planning scenarios in Matagorda County

II. Identify feasible interventions that can mitigate risk and vulnerability in the primary resources (water, energy, food) for Matagorda County.

III. Draw recommendations for future water allocations in Matagorda County, based on economic, social and environmental sustainability and the tradeoff implications for energy and food resources.

In short, the objectives are named as modeling (1), interventions (2), recommendations (3).

3.1 General Concepts

This work is a planning study focusing on future sustainability. In this regard, the year of 2070 was selected to provide a nearly 50-year projection that coincides with TWDB's statewide water plans. All data for water, energy, and food portfolio along with external relationships were projected to 2070 for the analytics. Possible severe conditions, such as drought, high population rate were taken into account. While modelling, water resources were limited to existing water rights and permits. Additionally, environmental flow requirements and recommended groundwater withdrawal values were considered as constraints. Reliability of water diversion for municipal and industrial consumption including energy production was selected at 100%, whereas agricultural water supply could be lower. In other words, municipal and industrial water users including energy producers would have sufficient water in any case scenario. Also, existing energy production, which is one of the major industrial activity in the county, was not sacrificed in any case.

Based upon these aforementioned principles, the WEF nexus model was drawn after analyzing data and describing system components, boundaries, stakeholders and observers. Therefore, the well-suited scenarios for the optimal water allocation, which might include interventions such as water-related infrastructure, were aimed to be presented. The WEF nexus framework of the study is formed as described below.

3.2 Framework

The framework is devoted to drawing recommended solutions for optimum water allocation analyses; as seen in Figure 32, this framework has 8 major steps to reach outcomes.

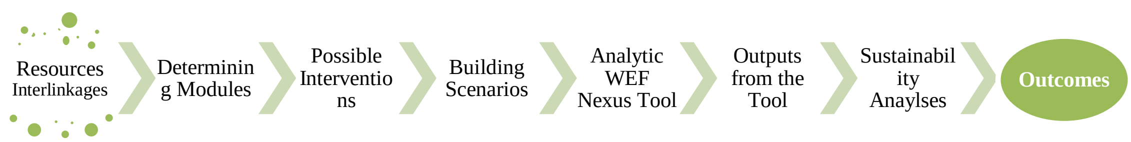

Figure 32. Flowchart of the Framework

Understanding the interconnections between primary resources was essential. Water-food, water-energy, and food-energy nexuses reflected the general resource allocation for the study area. Since, the nexus approach basically asserts each resource linked to each other, interdependencies of the resources were determined (i.e. water was needed for food production and irrigation requires energy). Available data related to interlinkages were inclusively analyzed to determine the main modules of the system. Modules basically drive the interlinkages and is difined a component of the existing system. A module could be an entire sector, industry, a governmental organization, municipality, etc. At the third stage, possible interventions that can build or increase sustainability were identified. Interventions aimed to be solution for the problem of the county. Most of the possible interventions studied were water related infrastructure: building a reservoir, treatment facility etc. A possible intervention should be feasible in the study area, but might be neither sustainable nor advisable. At the fourth step, interventions formed scenarios. A great number of scenarios could be built for analysis. A scenario meant a combination of interventions. The analytic WEF nexus tool, step six, could solve the complex, comprehensive interconnections between primary resources in accordance with various scenarios. The tool must include all elements upon which the allocation analysis was based. The next stage was outputs of the scenarios, which were acquired from the analytic WEF nexus tool. Based on scenarios, several kinds of outputs included water requirement, energy production and requirement, food production, cost, CO2 emission, and land allocated. The outputs did not produce results that could be directly applicable, as each scenario had several dimensions. Evaluations and assessments for the scenarios were carried out in the seventh step using the outcomes of each scenario. The developed sustainability and resource indexes were the key parameters of the sustainability analyses. Finally, water-centric, food-centric, cost-centric, environment-centric, and all-equal outcomes were presented based on the interests of various stakeholders and observers. The framework of the study is presented with details in Figure 33. Framework

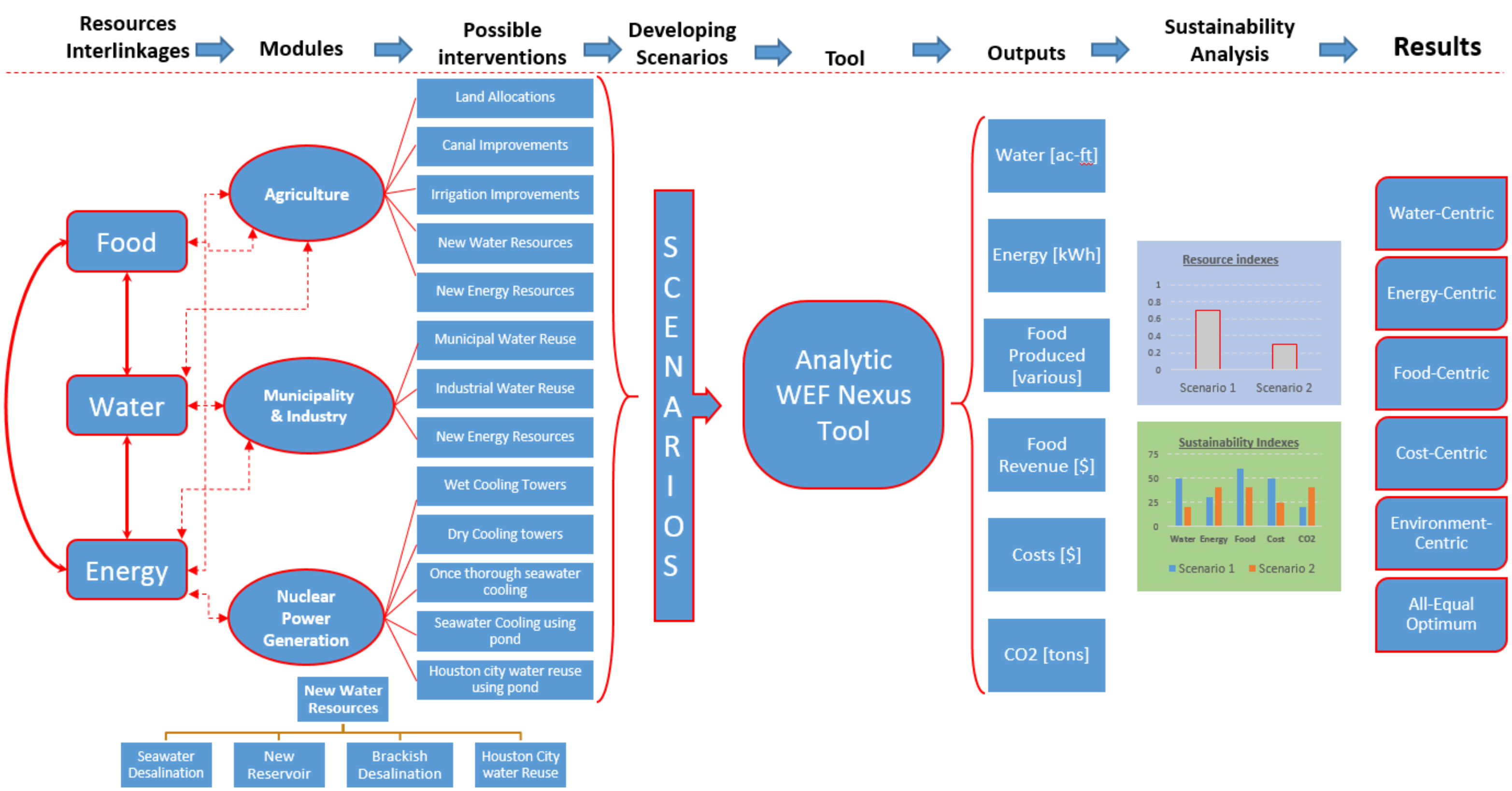

Figure 33. Framework

3.3 Modelling

Modelling is the first objective of this study. In this section, the links of the WEF nexus are introduced. Then, the modules of the existing WEF systems are presented. Lastly, the analytic WEF nexus tool which can quantifiably assess the scenarios is presented.

3.3.1 Interlinkages between Primary Resources

Working on the primary resources (WEF) and portfolios were essential to determine the scope of the study. Missing data, gaps in the literature, extreme future inaccuracy might have led to not consider some sectors for the study. For example, oil& gas production was not included. Figure 34 shows the interdependencies of the water-energy-food systems.

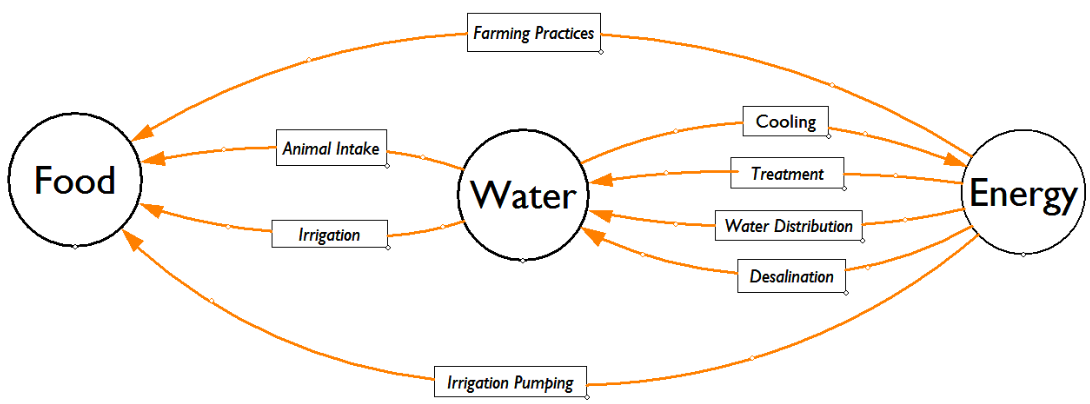

Figure 34. Interlinkages between Primary Resources

3.3.2 Modules

Modules as the drivers of the water-energy-food sectors were determined while focusing on the water, food, and energy portfolios and their interlinkages. Three modules that drive the primary resources in Matagorda were determined: Agriculture, Municipality & Industry, Nuclear Power Generation. These three modules pretty much cover all the interlinkages occurring in the county.

3.3.3 Analytic WEF Nexus Tool

3.3.3.1 Overview of the Analytic Tool

In order to represent current water allocations and make projections with new allocations for the future, a number of scenarios were developed across multiple sectors. Each scenario could be put into operation to determine the optimal selection of scenarios. The operation was performed using the tool, which basically used the scenarios as input to produce quantitative results (outputs) as presented in Table 9.

Symbol	**Parameter**	**Unit**
W	Water	Acre-feet (ac-ft)
E	Energy	Kilowatt-hours (kWh)
F	Food Produced	Based on the crop or animal (bushel, lb etc.)
R	Food Revenue	US dollars ($)
C	Costs	US dollars ($)
CO2	Carbon Footprint	Ton (ton)
L	Land Area	Acres (ac)

Table 9. The Parameters as Quantitative Results of the Tool

While some data for future projections for 2070 exist, more frequently, projected data must be developed. Historical values play an essential role, as they may indicate trends. Figure 35 below illustrates the steps of analytical tool as an overview.

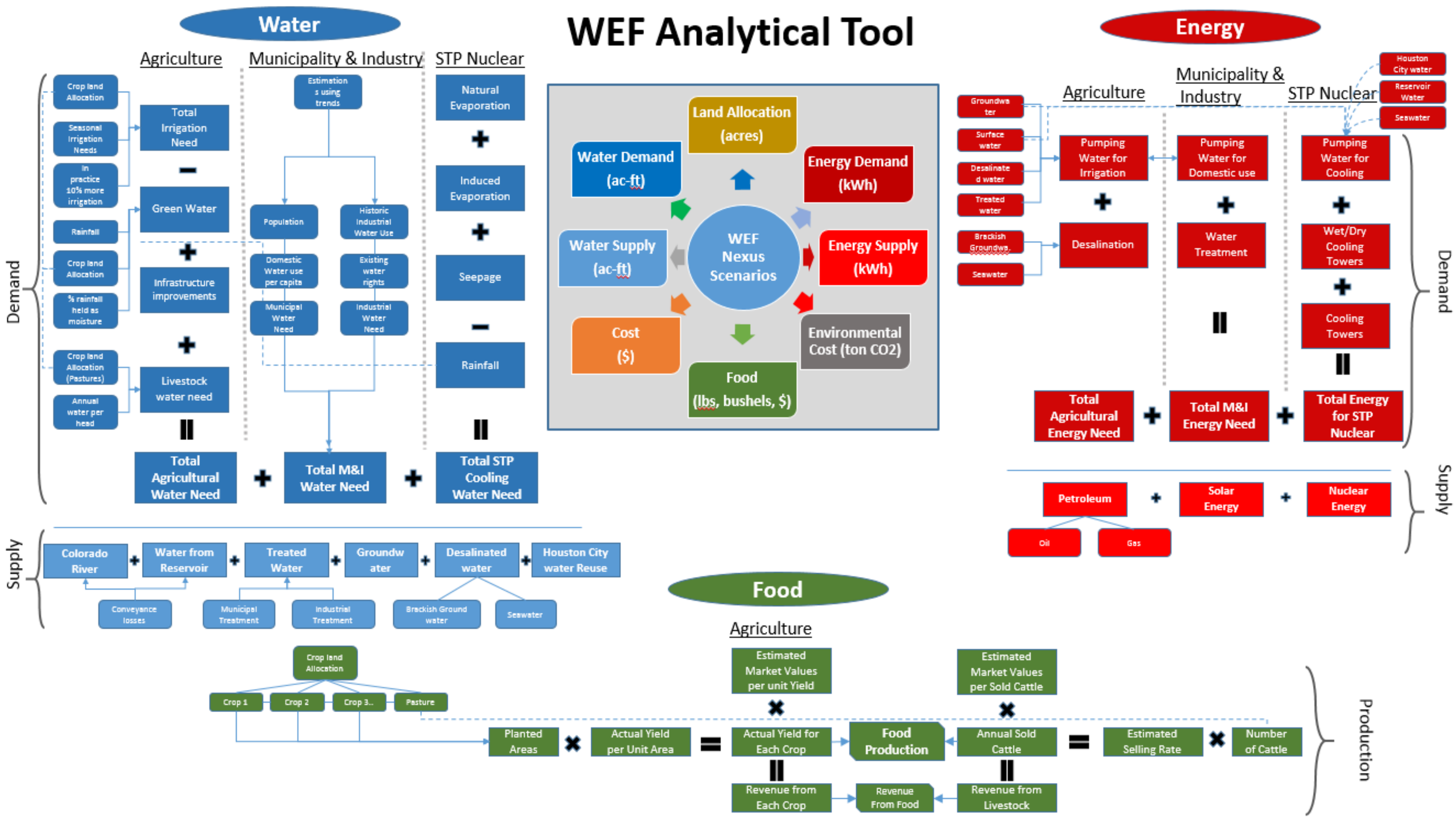

Figure 35. The Analytic WEF Tool

3.3.3.2 Analytics

The analytics of the study were mainly operated through the WEF nexus tool. In order to assess scenarios, analytic scenario outputs regarding water, energy, food, environment, and land were needed.

Water Calculations

Water is the indispensable element required for several purposes in the WEF nexus model. The water requirements considered in this study were those for agricultural production, municipal and Industrial demands, and energy generation.

$$\boldsymbol{W = W_{ag} + W_{m\&i} + W_{en}}$$

Where,

W= Total Water Requirements (ac-ft^3)

W_{ag}= Total agricultural water requirement (ac-ft^3)

$W_{m\&i}$= Annual M&I water use (ac-ft^3)

W_{en}= Water for energy production (ac-ft^3)

The water need of each crop was calculated using FAO's radiation method. The green water [see assumptions] contribution was extracted from the water needed for the irrigation need, and a 10% extra safety factor was applied for irrigation scheduling. An assumption was made regarding the green water calculations. According to this assumption, %75 percent of precipitation of is considered as green water while the rest can either be run-off or infiltrated. Water intake by animals was included in the total agricultural water requirement.

$$W_i = L_i \times S_i$$

$$W_{gi} = L_i \times P_i \times 75\%$$

$$W_{ii} = W_i - W_{gi}$$

$$W_t = \Sigma W_{ii}$$

$$W_c = 1.1 \times \Sigma W_t$$

Where,

W_c = Total water need for all of the crops totally for irrigation scheduling (ac-ft)

W_t = Total irrigation need (ac-ft)

W_i = Water need for a specific crop (ac-ft)

W_{gi} = Green water for a specific crop (ac-ft)

W_{ii} = Water need for irrigation scheduling for a certain crop (ac-ft)

L_i = Land allocated for a specific crop (acres)

S_i = Seasonal irrigation requirement for a specific crop (ac-ft)

P_i = Precipitation received during the growing period (feet)

Water for livestock is also another component of water requirement of agriculture. The average daily water intake by animals for drinking water and extra consumptions such as shower requirements in hot climate conditions, evaporation from water troughs, other ranch operations were taken into account.

$$W_l = (W_{ld} + W_{lo}) \times 365$$

Where,

W_{ld} = Daily drinking water per head (ac-ft)

W_{lo} = Other daily water requirements of livestock (ac-ft)

W_l = Total annual livestock water requirements (ac-ft)

The calculated annual water consumption of livestock is then added to agricultural water requirement.

$$\boldsymbol{W_{ag} = W_c + W_l}$$

Where,

W_{ag} = total agricultural water requirement (ac-ft)

Municipal water consumers included residential and commercial uses. Municipal demand was directly linked to population size and local trends which depend upon climate, season, culture, welfare, water availability, pricing, infrastructure, etc. As for industrial applications, the production process of goods and power, mining was considered as industrial use in this study. Water use amounts in industry varies tremendously, hence, each water consumption for an industrial company was calculated and taken into account separately.

$$\boldsymbol{W_{m\&i} = W_{mu} + W_{in}}$$

$$\boldsymbol{W_{mu} = W_{wpc} \times Pop}$$

Where,

W_{mu} = Municipal water use (ac-ft)

Pop = Population of the study area in a projected year (person)

W_{wpc} = Annual municipal water use per capita (ac-ft/person)

$W_{m\&i}$ = Annual municipal and industrial water use (ac-ft)

W_{in} = Annual industrial water use (ac-ft)

Water consumption for energy production varies depending on the generation type. In this study, only nuclear energy production was considering since it was the only energy resource consuming water resources. Cooling requirements included natural evaporation, seepage, induced evaporation and conveyance loses.

$$\boldsymbol{W_{en} = W_h + W_{ne} + W_{se} + W_{re}}$$

Where,

W_{en} = Water need for energy production (ac-ft)

W_h = Water evaporated due to heat dissipation (ac-ft)

W_{ne} = Natural evaporation from the pond (ac-ft)

W_{se} = Water goes to groundwater through seepage (ac-ft)

W_{re} = Released water from the cooling pond (ac-ft) (it is assumed zero due to missing data)

Energy Calculations

Energy is one of the major input of food production and water supply as well as cooling needs for nuclear plant. This study does not cover all energy consumption of the study area. Instead, it comprises consumption which initially have tradeoffs. Therefore, this study included energy needs due to agricultural crop production which covers machine farm operations and water distribution for irrigation, water supply to municipal and industrial uses, and pumping for cooling. Energy requirements include treatment and desalination process if applied. The analytics can be seen as followings.

$$\boldsymbol{E = E_{ag} + E_{m\&i} + E_{en}}$$

Where,

E= Total energy requirements (kWh)

E_{ag}= Total energy requirement for agriculture including livestock (kWh)

$E_{m\&i}$= Energy need for M&I water use (kWh)

E_{en}= Energy need for conveying cooling water to energy plant (kWh)

Along with water conveyance and treatment processes, agriculture consumes energy during farming operations: tillage, planting, cultivation, harvesting, fertilizing, forage blowing, stalk shedding, etc. Energy requirements vary with the proposed crop pattern. In the analytics, energy consumption of each crop was evaluated individually based on their water and farming operation needs then summed.

$$\boldsymbol{E_{fo} = E_{tillage} + E_{planting} + E_{cultivation} + E_{harvesting} + E_{miscelaneous}}$$

Where,

E_{fo} = Energy requirements for farming operations (kWh)

In this study, energy footprint of water resources was depended on the water resource. Conventional water resources studied in the study were groundwater and water diversion from the river and water from reservoir. Non-conventional water resources were brackish water, seawater, wastewater which had extra requirements to treat and desalinate.

Energy calculations for different water resources are up to water resource type. To express energy differences between various water resources, several factors were developed. When the factors were multiplied by the amount of water resource type, energy requirements were calculated.

$$\boldsymbol{E_{ag} = E_{sw} + E_{gw} + E_{desal} + E_{cw} + E_{fo}}$$

$$\boldsymbol{E_{sw} = \alpha_{sw} \times W_{sw}}$$

$$\boldsymbol{E_{gw} = \alpha_{gw} \times W_{gw}}$$

$$\boldsymbol{E_{desal} = \alpha_{desal} \times W_{desal}}$$

$$\boldsymbol{E_{cw} = \alpha_{cw} \times W_{cw}}$$

Where,

E_{ag} = Energy requirement for all agricultural activities (kWh)

E_{sw} = Energy requirement for transporting surface water from river or reservoir to farm (kWh)

E_{gw} = Energy requirement for pumping groundwater resources from underground (kWh)

E_{desal} = Energy requirement for desalinating and conveying sea or brackish water resources (kWh)

E_{cw} = Energy requirement for treating and conveying city water (kWh)

E_{fo} = Energy requirements for farming operations (kWh)

α = energy needed for unit volume of water, which might include desalination and treatment process depending on water type (kWh/ac-ft)

W = volume of water used for irrigation varying depending on water type (ac-ft)

Energy is needed for municipal and industrial water supply. For this study, surface water and groundwater were made available for domestic and industrial water consumption. Also, energy requirements due to treatment were applied when wastewater reuse process applied. It is important to note that municipal and industrial water treatments had different energy requirement per unit volume of water. The analytics of energy requirements as follows.

$$\boldsymbol{E_{m\&i} = E_{mu} + E_{in}}$$

$$\boldsymbol{E_{mu} = E_{pu-mu} + E_{tr-mu}}$$

$$\boldsymbol{E_{in} = E_{pu-in} + E_{tr-in}}$$

$$\boldsymbol{E_{tr-mu} = \alpha_{tr-mu} \times W_{tr-mu}}$$

$$\boldsymbol{E_{tr-in} = \alpha_{tr-in} \times W_{tr-in}}$$

$E_{m\&i}$ = Total energy needed for municipal and industrial water supply (kWh)

E_{mu} = Energy needed for municipal water supply (kWh)

E_{in} = Energy needed for industrial water supply (kWh)

$E_{pu\text{-}mu}$ = Energy needed for pumping municipal water supply (kWh)

$E_{pu\text{-}mu}$ = Energy needed for pumping industrial water supply (kWh)

$E_{tr\text{-}mu}$ = Energy needed for treating municipal water supply when reuse process applied (kWh)

$E_{tr\text{-}mu}$ = Energy needed for treating industrial water supply when reuse process applied (kWh)

Plus, energy is needed for energy production as well due to cooling of nuclear reactors studied in this study. Cooling is currently done through river water and groundwater resources. New interventions may use seawater and wastewater of city use as cooling. Each cooling system has different water and energy footprint. Cooling systems studied in the analytics are discussed in the Simulations chapter. The following equation shows total energy needed for cooling purposes.

$$\boldsymbol{E_{en} = E_{en-sw} + E_{en-sea} + E_{en-gw} + E_{en-cw}}$$

Where,

E_{en} = Energy need for conveying cooling water to energy plant (kWh)

E_{en-sw} = Energy need for conveying surface water (kWh)

E_{en-gw} = Energy need for conveying groundwater water (kWh)

E_{en-sea} = Energy need for conveying seawater (kWh)

E_{en-cw} = Energy need for conveying city wastewater (kWh)

As can be understood from the calculations above, several extra calculations were embedded in the abbreviations such as hydraulic calculations of conveyance, desalination and treatment processes. The details of calculations were expressed with details in appendices and simulations.

Food Calculations

Production varies depending upon the crop or livestock: this study is able to convert each crop production unit to a dollar currency for analysis. Thus, agricultural revenue is asserted as one parameter for sustainability analysis. Each crop has unique performance under diverse climate, soil type, irrigation amount and scheduling, water quantity, and fertilizer. When historic yields per unit area are studied, it is seen that crop yield per unit land rates tends to rise continually. Consequently, the formula below is developed and applied to project the food production for a given year. Increasing crop yield amounts are used.

$$\boldsymbol{Y_{Projected} = Y_{trend} - Y_{max} \times 0.5 + Y_{max}}$$

Where,

$Y_{Projected}$= Regulated trend of unit values for a certain crop yield (unit/ac)

Y_{trend}= Linear trend of unit values for a certain crop yield (unit/ac)

Y_{trend}= Maximum historic unit value for a certain crop yield (unit/ac)

The total amount of food can be found for a specific year as follows:

$$\boldsymbol{F_i = Y_i + L_i}$$

Where,

F_i= Total yield amount of a certain crop (unit)

Yi= Unit of projected yield value for a certain crop (unit/ac)

L_i= Land allocated for a certain crop (ac)

The yield amount varies mainly because of lack of irrigation. FAO's response to water method (Steduto, et al., 2012) is utilized to reflect real yield production with deficit irrigation.

The projection of the food prices is complicated as understood from the tremendous variable historic price values. Several factors, including climate, demand, oil price, inflation, policy, etc. influence the agriculture market. For more flexible and inclusive analysis, several food pricing options are available. Along with linear trend, historic maximum, average, and minimum agricultural market prices are available in the nexus tool. Total agricultural revenue value can be found as stated below.

$$\boldsymbol{R_i = F_i + U_i}$$

Where,

R_i= Revenue of a certain crop ($)

F_i= Yield of a certain crop (unit)

U_i= Unit of projected market value ($/unit)

$$R = \sum R_i$$

Where,

R= Total agricultural revenue ($)

Carbon Footprints

In the nexus framework, greenhouse emissions are considered as environmental cost. The model considers CO2 to assess sustainability of resource allocations. Greenhouse emission occurs due to the aforementioned energy consumption.

$$CO2 = CO2_{ag} + CO2_{m\&i} + CO2_{co}$$

Where,

CO2 = Total CO_2 emission (ton)

$CO2_{fo}$ = Carbon-dioxide emission due to agriculture sector (ton)

$CO2_{tr}$ = Carbon-dioxide emission due to M&I water use (ton)

$CO2_{co}$ = Carbon-dioxide emission due to cooling water conveyance (ton)

The energy consumed in various sectors may have different sources. For example, farming operations use diesel while pumping for irrigation is through electricity produced in the nuclear plant. Each consumption is evaluated independently. Energy sources considered in this study are fossil fuels, nuclear, solar.

$$CO2_i = E_i + \Delta_i$$

Where,

Δ = Tons of CO_2 per kJ energy (ton/kJ). It depends on energy sources.

E_i = Various energy consumptions in the nexus (kJ)

Financial Costs

Financial analysis is one of the major component of the nexus framework. Costs occur due to the nexus interventions. Strategy project and investment costs should be annualized for the analyses since all other outputs are annual values. Technological implementations, infrastructural investments, and improvements of existing system are considered. A discount rate must be selected in order to keep the same analysis consistent across all projects. Applying the most recent construction costs is the convenient way for the analysis.

$\mathbf{C = \Sigma C_i}$

C = Total costs

C_i = Cost of each strategy projects considering capital and annual costs.

Land Allocations

Land is directly linked to agricultural production, including livestock, in the study. Type of cropping system and altering current crop combinations may decrease water, energy, and food outputs. Effects of urbanization can be reflected in the scenarios. Historic decrease in cropland and pastureland give the nexus a sign for future projections.

$$\boldsymbol{L = \sum L_i}$$

Where,

L = Total crop and posture lands (ac)

L_i = Land allocated for a specific crop or posture (ac)

During operation, land allocation is used as input through interventions (see simulations).

3.4 Interventions

Interventions are the levers of the primary resources and aimed mitigating resource insecurity and ensuring a more sustainable future. Most of the interventions studied in this study were water-related infrastructure. Improving on-farm irrigation system, building a new reservoir, improving water distribution infrastructure, altering cooling system of nuclear plant could be counted as some of the possible interventions. Before building scenarios, pre-feasibility study was carried out to determine feasible interventions. Only feasible solutions as possible interventions were put in scenarios which would further be analyzed.

After working on the study region exclusively, possible feasible interventions were determined. Several ones were available to mitigate primary resource insecurity and ensure a more sustainable future. However, deciding on the ultimate interventions at multiscale levels required inclusiveness of the influences of other resources and stakeholders. Along with current practices, possible interventions were determined for the modules selected for this study are shown in Table 10. Pre-feasibility study was a must to determine feasible interventions that can be further analyzed. For example, once through seawater cooling (direct) had been an option at first but it was removed from the sustainability analysis after the analytics of the tool indicated that cooling system required half of total energy production of the plant. Thus, only feasible interventions were expressed in the Table 10 below.

<table>
<tr><th colspan="3">Agriculture</th><th colspan="2">M & I</th><th>Nuclear Power Gen.</th></tr>
<tr><td>Land Allocation*</td><td>Irrigation Improvements</td><td>Water Resources</td><td>Municipal Water Reuse</td><td>Industrial Water Reuse</td><td>Cooling System</td></tr>
<tr><td rowspan="2">(1) More Ag. Land, Less Water Demanded Cropping</td><td rowspan="5">Improvements on water conveyance systems</td><td rowspan="2">New Reservoir</td><td rowspan="8">Water Treatment and Ruse As 50% or 80% of consumed</td><td rowspan="8">Water Treatment and Ruse As 50% or 80% of consumed</td><td rowspan="2">Water from New Reservoir</td></tr>
<tr></tr>
<tr><td rowspan="2">(2) More Ag. Land, More Water Demanded Cropping</td><td rowspan="2">Seawater Desalination</td><td rowspan="2">Once through seawater</td></tr>
<tr></tr>
<tr><td rowspan="2">(3) Current Land, Less Water demanded Cropping</td><td rowspan="2">Brackish Desalination</td><td rowspan="2">Seawater using pond w/out Reservoir water</td></tr>
<tr><td rowspan="3">Improvements on- farm Irrigation Systems</td></tr>
<tr><td rowspan="2">(4) Urbanization, Current Allocation Distribution</td><td rowspan="2">Houston Reuse</td><td rowspan="2">Houston Reuse water</td></tr>
<tr></tr>
<tr><td colspan="6">Solar Farm</td></tr>
</table>

Table 10. Possible Interventions

While simulating scenarios (combinations of possible interventions), there were undoubtedly constraints, financial limitations, boundaries, priorities, existing policies and so on that should be taken into account. The complexity of these implementations could be evaluating them using a tool. Tool operated with scenarios which consist of interventions.

3.4.1 Scenarios

Using possible interventions, 25 scenarios were developed. Each scenario was consisting of possible scenarios. The optimal and recommended scenarios were determined based on the analyses of scenarios' prospective positive and negative contributions to water, energy, food portfolios and financial, environmental cost outputs. The scenarios were processed in the tool which promotes numerical outputs for each scenario. In other words, the determined scenarios were put in the tool to get analytic results which would then be analyzed. Also, a base scenario which had no possible intervention (called business as usual) was developed. The Figure 36 below illustrates 25 different scenarios which include possible interventions.

Modules	Interventions			Scenarios																								
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Agriculture	Land Allocation*	Current Ag. Land and Crop Allocation		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓															
		More Ag. Land and More Water Demanded Crops												✓	✓	✓	✓	✓										
		More Ag. Land and Less Water Demanded Crops																	✓	✓	✓	✓	✓					
		Current Ag. Land and Less Water Demanded Crops																						✓	✓	✓	✓	✓
	Irrigation Applications	Conveyance System Improvement		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓
		On-farm system Improvement				✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓		✓	✓	✓	✓		✓	✓	✓	✓
	Water Resources	New Reservoir			✓	✓	✓	✓	✓		✓	✓	✓		✓	✓		✓		✓	✓	✓	✓		✓	✓	✓	✓
		Seawater Desalination	50,000 (ac-ft)										✓				✓											
			100,000 (ac-ft)				✓			✓						✓		✓			✓	✓				✓		
		Brackish Groundwater	50,000 (ac-ft)					✓		✓		✓				✓							✓					
			100,000 (ac-ft)										✓				✓	✓		✓		✓					✓	✓
		Houston Water Reuse	50,000 (ac-ft)																									✓
			100,000 (ac-ft)								✓										✓							
			200,000 (ac-ft)														✓	✓					✓					
M & I	Municipal Water Reuse	Water Reuse	50%										✓		✓					✓	✓							
			80%		✓				✓	✓	✓	✓				✓	✓	✓				✓	✓		✓	✓	✓	✓
	Industrial Water Reuse	Water Reuse	50%												✓					✓	✓							
			80%		✓				✓		✓	✓						✓				✓			✓		✓	
Nuclear Generation	Cooling System	Current Practice		✓	✓		✓							✓		✓			✓	✓			✓	✓	✓			
		Water from reservoir					✓	✓	✓				✓			✓		✓		✓		✓	✓		✓		✓	
		Seawater using pond						✓	✓	✓		✓	✓				✓	✓				✓				✓	✓	
		Houston water reuse				✓					✓				✓						✓							✓
	Solar farm										✓	✓	✓			✓		✓			✓	✓	✓			✓	✓	✓

Figure 36. Scenarios and Possible Interventions Embedded in the Scenarios

3.4.2 Quantitative Outputs

The WEF nexus tool operates analytics. As results of which, numerical outputs were presented for each scenario. For each scenario, several numerical outputs due to interventions were gained: water demand and use, energy demand and use, food production, food revenue, costs, carbon emission and so on (see Figure 37. Scenarios and Outputs via WEF Nexus Analytic Tool). Even if these numerical outputs give some ideas, the final analysis needs to be carried out to figure out most recommended scenarios. A sustainable analysis method was developed as stated below.

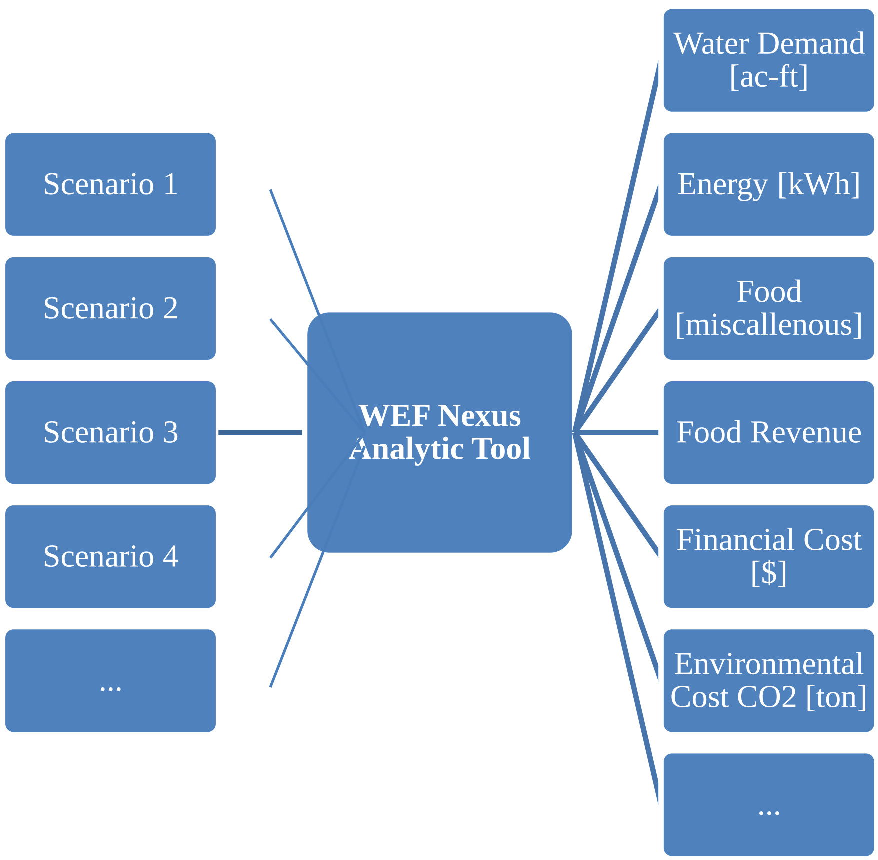

Figure 37. Scenarios and Outputs via WEF Nexus Analytic Tool

3.5 Recommendations

To analyze each scenario and figure out the best sustainable scenarios in terms of sustainability, a unique sustainability analyses methodology was developed. In short, after operated 25 scenarios as seen in Figure 36, various output parameters were obtained. Then, normalization process was then applied to determine resource indexes. Each resource index was multiplied by weighting factors, which reflect the perspectives of stakeholders or observers. Consequently, the sustainability indexes were ranked to indicate water-centric, energy-centric, food-centric, cost-centric, environment-centric, overall optimum scenarios.

3.5.1 Resource Indexes

After operated scenarios in the WEF nexus tool, output parameters (demands of water, energy, cost, agricultural revenue, carbon-dioxide emission and so on) of each scenario were presented. Each quantitative output had a unit depending upon the resource. Normalization operations were carried out to standardize various units. The resource indexes were calculated using the formulas below. The values ranges from 0 to 1.

$$\boldsymbol{Resource\ index_i = \frac{Output_i}{max(Output_i)}};$$

$$\boldsymbol{W_i = \frac{W_i}{max(W_i)}}, \quad \boldsymbol{E_i = \frac{E_i}{max(E_i)}}, \quad \boldsymbol{R_i = \frac{R_i}{max(R_i)}}, \quad \boldsymbol{C_i = \frac{C_i}{max(C_i)}}, \quad \boldsymbol{CO2_i = \frac{CO2_i}{\max(CO2_i)}}$$

3.5.2 Weighting Factors

Weighting factors were applied to five different resources indexes (already normalized values). The sum of the weighting factors should be 1.0. The highest value in the column of Table 11 was given to the desired perspective. Therefore, the stakeholder's perspective can be reflected.

Outputs	Symbol	Water-Centric	Food-Centric	Enviro-Centric	Cost-Centric	All-Equal
Water	W	a1	b1	c1	d1	e1
Energy	E	a2	b2	c2	d3	e3
Food	R	a3	b3	c3	d5	e5
Cost	C	a4	b4	c4	d7	e7
CO2	CO2	a5	b5	c5	d9	e9
	Total:	1.00	1.00	1.00	1.00	1.00

Table 11. Weighting Factors

The weighting factors used in this study indicated in Table 12.

Output Parameters	Symbol	Water-Centric	Energy-Centric	Food-Centric	Cost-Centric	Environ-Centric	All Equal
Water Demand (m^3)	W	0.40	0.15	0.15	0.15	0.15	0.20
Energy Demand (kWh)	E	0.15	0.40	0.15	0.15	0.15	0.20
Agricultural Revenue ($)	R	0.15	0.15	0.40	0.15	0.15	0.20
Cost ($)	C	0.15	0.15	0.15	0.40	0.15	0.20
CO2 Emission (ton)	CO2	0.15	0.15	0.15	0.15	0.40	0.20

Table 12. Preferred Weights

This study therefore is able to recommend different scenarios for various users since 6 different perspectives were reflected as seen in the table above. Weighting factors were applied to reflect the perspectives of stakeholders or observers.

3.5.3 Sustainability Indexes

To rank scenarios, sustainability indexes of 6 different perspectives (water-centric, energy-centric, food-centric, environment-centric, cost-centric, all-equal) were developed for each scenario. In doing so, for higher sustainable scenarios, water, energy, cost demands and carbon-dioxide emission were expected to be less whereas agricultural revenue is high. Therefore, resource indexes of agricultural revenue were made negative and then summed in the sustainability index formula as seen below.

$$\boldsymbol{Sustainability\ Index_i = 1 - \left(\sum Wf_i \times Resource\ Index_i\right)}$$

3.5.4 Outcomes

Outcomes of this study are final recommendations for users [stakeholders, observers, policy makers]. Based on 6 kind different sustainability indexes, scenarios were ranked. Each kind of sustainability index indicates the stakeholder preferences. Indexes ranges from least sustainable, 0 to most suitable. Therefore, water, energy, food, cost, environmental -centric and optimal [all equal] scenarios in terms of sustainability of each were determined and presented.

3.6 The Overview of the Nexus Model

Figure 38 shows the layout of the nexus model for case of Matagorda County. The connections between the water, energy, and food tenants of the nexus with the primary resources were illustrated. Also, possible interventions that can mitigate risks and vulnerabilities of the primary resources were indicated in the rectangles. It was assumed that current conditions in Matagorda County would remain at their current state and only the addition of new scenarios which include interventions could improve the sustainability of the county.

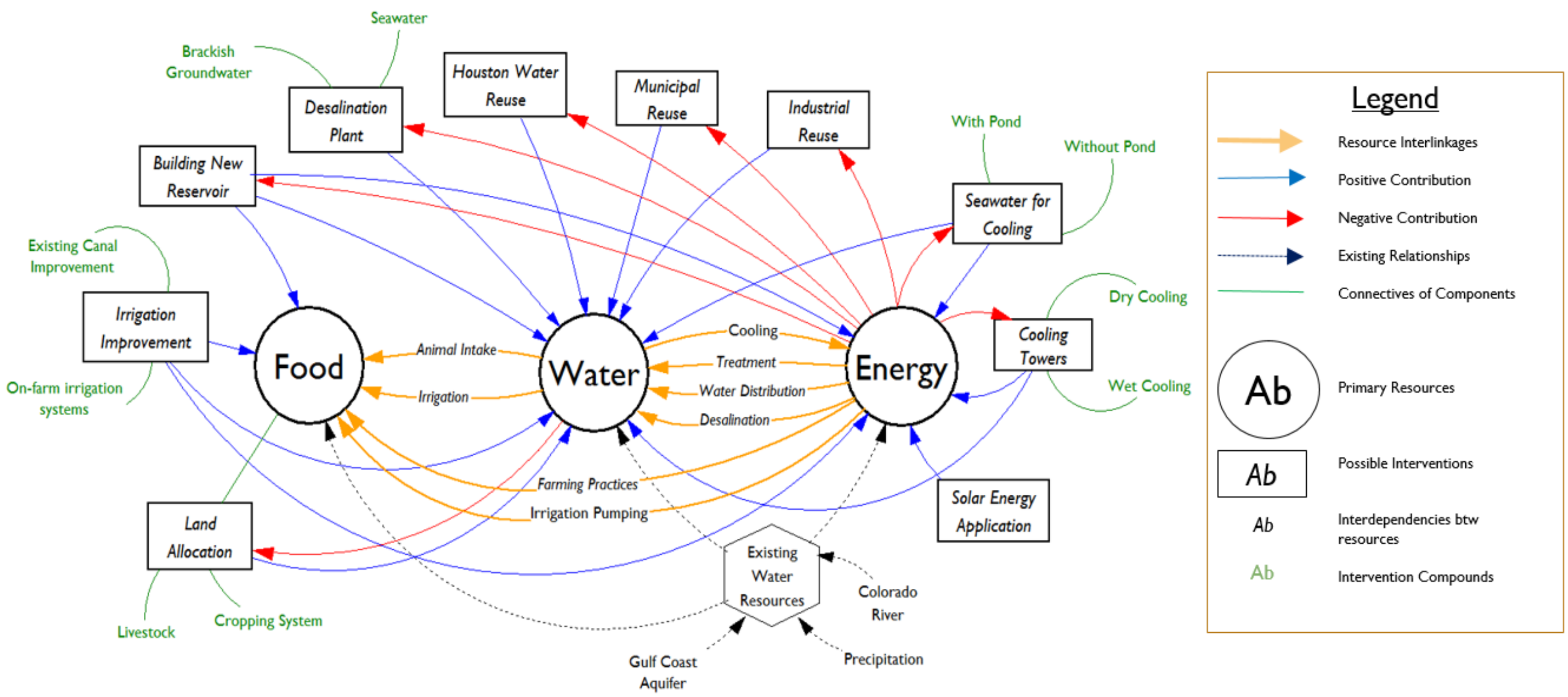

Figure 38. Schematic Overview of WEF Nexus Model and Interlinkages of Possible Interventions

4. DATA ANALYSES AND ASSUMPTIONS

One of the objectives of this study, modelling, required several kind of data sources to be run the proposed model. In this chapter, data needed and the sources are described along with the processes of the collected data in details. In doing so, utilized international, national and regional agencies which provide data are presented as well as some studies having suitable information for the case. However, in some circumstances, assumptions were required to be made.

4.1 Data Needed Description

The nexus study aims to bring most sustainable future scenarios. Since the study focused to project the year of 2070 [see 3.1 General Concepts], all the data must have reflected the future projections and be feasible. Historical values for population, climate, and production and consumption of primary resources played key roles for projections. Historical linear, polynomial, exponential, and power regressions trends were utilized to estimate future trends.

Historic water allocation values and existing water rights and permits for each module (Agriculture, Municipality & industry, STP Nuclear Power Generation) of the nexus system of the county were essentially and required for the analytics. As stated in methodology, no violations were made to existing water rights and permits. Beside future projections, current practices for each module were needed to have a base scenario.

4.1.1 Data Needed for Agriculture

Al the data needed for agriculture sector including livestock is listed below:

- ✓ Climate data was essentially required for food production calculation processes. For this study, as described in methodology, harsh climatic conditions were utilized.
- ✓ Historic planted land areas by crop types and historic livestock inventory and selling records were also needed for food and water interlinkages.
- ✓ Data for farming practices which depends on crops local trends were needed to help figure the energy portfolio of agriculture out.
- ✓ Historic market prices [US dollars per unit food] were required for converting food production into dollar values
- ✓ Yield values were also based upon several things such as irrigation scheduling, climate, anticipated genetic technology improvements.
- ✓ Data for existing irrigation system [water loses and the efficiencies] including systems of on-farm infrastructure and large scale conveyance were needed
- ✓ This study also considered desalination as a possible intervention Matagorda County due to its adjacency to the Gulf of Mexico. Parameters such as salinity rate, distances between intake station, plant, croplands, plant costs and energy requirements were essential.
- ✓ Bringing water for agricultural purposes from urban areas could be one of the possible interventions. However, assessing the use wastewater of urban areas necessitated several parameters such as wastewater treatment, the distance between the city and the study area, pipe and pump selections, needed water amount and so on. The closest metropolitan area which have high amount of wastewater near to Matagorda County was the city of Houston. Along with data of Houston wastewater and conveyance feasibilities were needed for the tool.
- ✓ Livestock was one of the major component of the agriculture. To figure out the financial potential of the county, annual sales records of animals were required.

- ✓ Finally, historic market prices of animals and crops were needed for bringing different agricultural values into US dollar currency.

4.1.2 Data Needed for Municipality and Industry

All required data for municipal and industrial module is seen as a list below:

- ✓ Domestic water use is directly linked to population. Therefore, population growth for the projected year was needed.
- ✓ Another player to calculate domestic water use was trends in the study area. This included indoor and outdoor water use. Historic estimated water use per capita was needed to project future in this regard.
- ✓ Industrial water use is up to the industrial activities of the study area. Thus, water use trends of each company were needed to determine total water consumption of the industrial activities.
- ✓ Current water infrastructure could help determine energy footprint of water distribution which reflected one of the main the tradeoffs.
- ✓ In case treatment applied for water reuse, the features of wastewater were needed to be investigated such as water quality and quantity. The treatment process was also variable depending upon where the water wasted.

4.1.3 Data Needed for Nuclear Power Generation

Nuclear Power Generation is one of the three modules of the WEF nexus system of this study. Data needed for the module is seen in the followings:

- ✓ Even though nuclear power generation is an industrial activity, due to its direct contribution to energy production, it was evaluated individually. Current and anticipated amounts of energy productions were needed.
- ✓ Cooling system for todays and proposed for the future was needed to be analyzed.

- ✓ Data for water consumption for cooling in harsh climatic conditions were needed to determine water requirement of the plant. Climate data played a key role in doing so.
- ✓ Other hydrological and geological data of the plant site and cooling pond such as seepage were needed.
- ✓ Energy and financial cost data of possible cooling technologies were needed.

4.2 Data Sources and Processes

A large variety of data sources and types were needed as described above for Matagorda County case study. Data for M&I water demand, groundwater depth, and existed and planned conveyance system was provided from TWDB. Data for local food production and its water use trends were borrowed from Department of Agriculture (USDA) as well as market values of crops and livestock. Various climate data available from National Oceanic and Atmospheric Administration (NOAA) was utilized. Data regarding nuclear energy production and its water consumption was obtained from (International Atomic Energy Agency) IAEA and United States Nuclear Regulatory Commission (USNRC). Carbon emission data while consuming energy was provided from Energy Information Administration (EIA). National Renewable Energy Laboratory's (NREL) the System Advisor Model (SAM) was selected as an auxiliary tool to determine available the most recent solar energy applications. To bring historical project cost values to today or future projection required some financial data from Bureau of Reclamation (USBR), and USDA. In addition to these, several studies and research published by scientists or institutions were utilized for needing data regarding population, wastewater from Houston, recommended groundwater withdrawals, water treatment and desalination, farming practices, existed water infrastructure.

Required data for analytics borrowed from various federal or international agencies and local studies and research were described below:

4.2.1 Population

Unlike the inclination of the state of Texas, the population of Matagorda County has showed downward trend in the recent years. However, it was anticipated that the state population growth will increasingly continue (TWDB, 2016a). While projecting the year of 2070, Texas Demographic Center's Projection tool which provides projected population was utilized along with its linear trend (Texas Demographic Center, 2016b). The highest migration expectation was selected for projections. Table 13 below includes the projected population values.

Year	Population
2020	39,166
2030	41,226
2040	42,548
2050	43,570
2060	44,296
2070	44,815

Table 13. Projected Populations (Adapted Based on the Population Trend in The Texas Demographic Center Tool (Texas Demographic Center, 2016b))

4.2.2 Climate

Temperature and precipitation data was from NOAA's National Climatic Data Center (NCDC) website. One of the 10 climate divisions of Texas, named Upper Coast, was selected for this study as Matagorda is in Upper Coast climatic region. The recorded driest year, 2011, was selected and presented in Table 14 and Table 15 for all necessary climatic data in this study (NOAA - NCDC, 2016b).

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
51.7	55.8	66.3	73.1	76.7	84.2	85.9	88.1	81.6	71	63.7	55.4

Table 14. The Temperature Data of the Recorded Driest Year (2011) of Upper Coast (Source: NOAA - NCDC, 2016)

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
3.62	0.74	1.21	0.21	1.01	2.29	2.91	0.89	1.71	2.72	2.43	3.9

Table 15. The Precipitation Data of the Recorded Driest Year (2011) of Upper Coast (Source: NOAA - NCDC, 2016)

4.2.3 Water Rights

Data on active surface water rights were obtained by TCEQ, responsible for issuing surface water rights in Texas. TCEQ provides information of the rights including the name of owner, usage type, priority year and the annual permitted diversion amount (TCEQ, 2016) [see appendices].

As for groundwater use, modeled available groundwater for Matagorda County by Groundwater Management Area 15 was utilized in order to not damage environmental constraints (TWDB, 2015).

4.2.4 Crop Pattern

Historical planted acres are borrowed from USDA's censuses and annual surveys (USDA - NASS, 2016a). The charts in Figure 23. Historic Matagorda County Acres of

Cotton Planted (Source: USDA Surveys), Figure 23, Figure 24, Figure 25, Figure 26, and Figure 27 shows how much acres allocated for major crops planted in Matagorda.

Total cropland and pastureland values of Matagorda County provided flexibility while building scenarios since farmers of Matagorda could change their pastureland to farmland or vice versa if they wish. As can be seen from Figure 21, most of the agricultural land was utilized as pastureland. In this study, 2014 values of crop pattern which was the most recent available data and pretty much reflects the recent drought was utilized. Also, crop pattern interventions such as the values of 1980 for the purpose of showing higher water-demanded agriculture processor in scenarios and a newly developed crop pattern values for lower water-demanded were applied. The Table 16 below shows different interventions that are put to several scenarios.

Crop Pattern	**Corn**	**Cotton**	**Rice**	**Sorghum**	**Soybeans**	**Total**
The year of 2014	33,800	32,400	4,000	31,800	6,100	108,100
The year of 1989	3,900	8,900	57,000	53,100	52,000	174,900
High land & low water use	40,000	30,000	2,000	40,000	10,000	122,000
Low land & low water use	25,000	25,000	2,000	25,000	5,000	82,000

Table 16. Crop Patterns Studied in the Study (values in acres) (Source: USGS Surveys for 1989 and 2014)

4.2.5 Livestock

Data needed for the projection of the number of livestock was borrowed from USDA's censuses and annual surveys. USDA also provides the amount of annual sales of animals (USDA - NASS, 2016a). The number of cattle projected for the year of 2070 is 62,364. Historical values showed that %50.6 of existing cattle have been sold and the ratio has been pretty much stable for decades, with some negligible values (USDA - ERS, 2016).

4.2.5.1 Water Requirements of Livestock

A study regarding water intake of cattle is derived from a study published by University of Nebraska. Estimated daily water intake was adopted to Matagorda County since it had been prepared for the weather of the state of Nebraska (Guyer, 1977).

4.2.5.2 Market Values for Livestock

Historical monthly livestock prices ($/head) starting from 2000 was borrowed from USDA's "Livestock & Meat Domestic Data" website and presented in Figure 39. While converting monthly price to annually, only the first month of the years was evaluated (USDA - ERS, 2016).

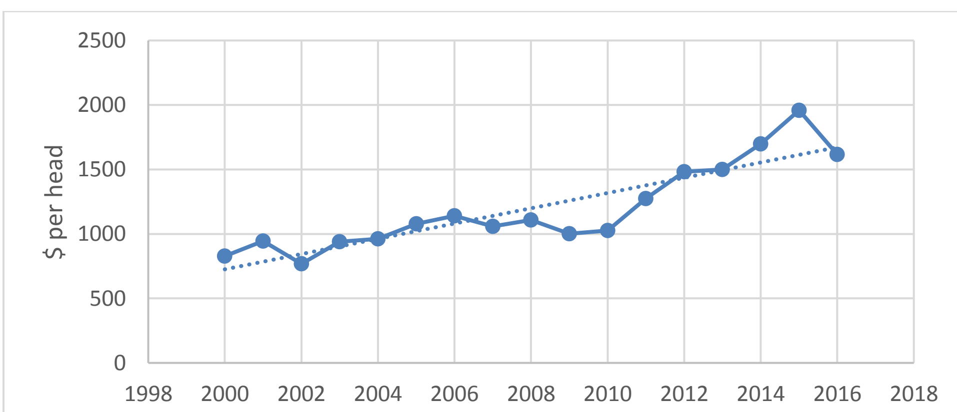

Figure 39. Livestock Sales Price Annually (the Month of January of Each Year) (USDA - ERS, 2016)

4.2.6 Crop Water Requirements: FAO Radiation Method

The method to calculate seasonal crop water requirements was Radiation Method as defined in FAO's *FAO Irrigation and Drainage Paper 24* (Doorenbos & Pruitt, 1977). The reason why Radiation method had been selected among other methods was that the method was very suitable for the available data for analytics in Matagorda County. FAO's paper provides Crop Coefficient (Kc) values for each crop to calculate crop evapotranspiration rate.

Cloud cover, relative humidity, and wind speed data, which had been needed for radiation method were barrowed from NCDC's website. The station in Palacios Municipal Airport, the ID number is 72255512935, was selected. 2011's hourly values for whole year were utilized (NOAA - NCDC, 2016a).

4.2.7 Green Water

Green water was described in this study as water coming through precipitation and going back to the hydrologic cycle via evapotranspiration. The purpose of accounting green water was to take the contribution of precipitation to irrigation into account. However, it is not quite certain how much percentage of precipitation becomes green water. It depends on several parameters such as slope, dynamic and physical features of soil, geological conditions, rainfall duration and intense. Therefore, an assumed precipitation values was carried out for green water calculations [see assumptions].

4.2.8 Farming Practices

Farming operation practices may change region by region. For the estimated fuel requirements of major crops (except rice), a study titled as "*Estimated Fuel Requirements for Selected Farming Operations"* done by University of Georgia was used as reference (UGA Extension Engineering, 2016) [see appendices]. As for rice, fuel requirement was borrowed from a USDA's report, titled "*Characteristics and Production Costs of U.S. Rice Farms"* (Livezey & Foreman, 2004) [see appendices]. The Table 17 below shows estimated fuel consumption of five major crops used in this study.

Crops	**Diesel (gal/acre)**
Corn	6.9
Cotton	13
Rice	37.3
Sorghum	4.7
Soybeans	6.5

Table 17. Estimated Fuel Consumption of Different Crops per Acre (Adapted Based on a Study Entitled "Estimated Fuel Requirements for Selected Farming Operations and Characteristics" and "Production Costs of U.S. Rice farms" Published by UGA and USDA Respectively)

4.2.9 Yield Response to Deficit Irrigation

Due to the availability of water for agriculture or management practices, farmers may (most likely during drought conditions) grow their crops with lack of irrigation or even without irrigation. The crop yield harvested from the field when deficit irrigation applied was calculated based on FAO water production function published in *"FAO 66: Crop Yield Response to Water"* (Steduto, et al., 2012). The function of yield response to lack of water was used in the tool to express the yield response.

$$\left(1 - \frac{Y_a}{Y_x}\right) = K_y \left(1 - \frac{ET_a}{ET_x}\right)$$

Where,

Y_x = maximum yield (unit for a certain crop)

Y_a = actual yield(unit for a certain crop)

ET_x = Maximum evapotranspiration (feet)

ET_a =Actual evapotranspiration (feet)

K_y = a yield response factor that represents the effect of the lack of irrigation (Ky values were borrowed from FAO Irrigation and Drainage Paper 33 (Doorenbos & Kassam, 1979) and presented as seen in Table 18.

Crops	Seasonal Ky values from FAO 33 (Doorenbos & Kassam, 1979)
Corn	0.85
Cotton	1.25
Rice	1.125
Sorghum	0.85
Soybeans	0.9

Table 18. Ky Values and Actual Yield per Acre (Source: FAO Irrigation and Drainage Paper 33)

Using the equation above and Ky factors, actual yields were calculated. Based on the agricultural supply percentage, the tool determines the crop yield for each of the crops.

4.2.10 New Water Resources

There are currently 2 water resources available for Matagorda County: Direct diversion from Colorado River and Gulf Coast Aquifer. A new reservoir which is expected to supply water for agriculture (LCRA, 2015) is under construction near to Lance City. The water supply from the prospective reservoir was one of the possible interventions that can build or increase of the sustainability of the study area. As non-conventional water resources, three water resources were made available for Agricultural water consumption: Reuse water of city of Houston, brackish water from some groundwater resources, and seawater with desalination. The model included various water resources and considered their financial and energy costs as well as water volume. Table 19 shows the possible water resources which can be applied as interventions in the future scenarios and their values for agricultural water consumption in Matagorda County.

Conventional Water Resources						
River Diversion	From 0 to 38,096					
Groundwater	From 0 to 45,896					
New Reservoir	0	35,000				
Non-Conventional Water Resources						
Houston Reuse	0	10,000	25,000	50,000	100,000	200,000
Desal Sea	0	10,000	25,000	50,000	100,000	
Desal Brackish	0	10,000	25,000	50,000	100,000	

Table 19. The Amount of Water Resources Available for the Analytic Tool (Values in ac-ft)

4.2.10.1 Desalination of Seawater & Brackish Groundwater

Needless to say, desalination requires a significant amount of energy considering todays technological advancement. The water volume values used for scenarios as possible interventios can be seen in the Table 19. The Amount of Water Resources Available for the Analytic Tool (Values in ac-ft). Besides energy required for desalination process, energy costs due to water conveyance were taken into account. Energy use of desalination of seawater from Gulf of Mexico and Brackish water from groundwater resources were referenced from WateReuse Association's "*Seawater Desalination Power Consumption"* publication (Desalination Committtee, 2011) and added to Table 20 below.

Energy Use of Water Supply Alternatives	**Power Consumption (kWh/kgal)**	**Selected Value Average (kWh/kgal)**	**Power Consumption (kWh/ac-ft)**
Brackish Water Desalination	3.0 – 5.0	4	1303.4
Desalination of Gulf of Mexico Water	9.1 – 13.2	11.15	3633.2

Table 20. Unit Energy Use of Desalination of Seawater and Brackish Groundwater (Source: WateReuse (Desalination Committtee, 2011))

The study also takes financial cost values of as one of the major parameters on decision making. Cost for desalination associates with capital investment of desalination plant. As reference for cost values, a study named *"Estimating the Cost of Desalination Plants Using a Cost Database"* (Wittholz, et al., 2008) was utilized and the cost values were then brought into 2016 values using USBR construction cost trends (USBR, 2016). Financial cost estimation was dynamic unlike energy use estimations, so it required the use of different trends instead of linear trends. The study shows that financial unit cost values decrease when the plant size increases. The principle was reflected into the study based on the proposed plant size when a scenario included a desalination plant. Table 21 Table 22 provides detailed information regarding desalination cost values used in the study.

Seawater Desalination Plant Size Capacity (m3 /d)	**Capacity (ac-ft/yr)**	**Capacity (gal/yr)**	**2008 Capital cost ($)**	**2016 Capital cost ($)**
10,000	2,959	964,227,682	20,100,000	24,015,584
50000	14,796	4,821,138,409	74,000,000	88,415,584
275000	81,375	26,516,261,249	293,000,000	350,077,922

Table 21. Seawater Desalination Cost Values (Adapted from a Study Entitled "Estimating the Cost of Desalination Plants Using a Cost Database" (Wittholz, et al., 2008). 2008 Values Converted into 2016 Values Using USBR Construction Cost Trends (USBR, 2016))

Brackish Groundwater Desalination Plant Size Capacity (m3 /d)	**Capacity (ac-ft/yr)**	**Capacity (gal/yr)**	**2008 Capital cost ($)**	**2016 Capital cost ($)**
10,000	2,959	964,227,682	8,100,000	9,677,922
50000	14,796	4,821,138,409	26,500,000	31,662,338
275000	81,375	26,516,261,249	93,500,000	111,714,286

Table 22. Brackish Groundwater Plant Cost Values, (Adapted from a Study Entitled "Estimating the Cost of Desalination Plants Using a Cost Database" (Wittholz, et al., 2008). 2008 Values Converted into 2016 Values Using USBR Construction Cost Trends (USBR, 2016))

4.2.10.2 Houston Wastewater Reuse for Irrigation

The closest large amount of city water for Matagorda County can be found from Houston metropolitan area. Most of the wastewater treated by the city of Houston is discharged into Galveston Bay. Houston water use and wastewater production data was taken from the City of Houston Water Conservation Plan (City of Houston, 2014) and analyzed to make projections. In 2013, there was 79,840,874,000 gallons (approximately 243,000 ac-ft) treated wastewater available. Only 184 ac-ft of it was used for reuse activities. Since the population of Houston is expected to be higher in the year of 2070, more than 200,000ac-ft water is expected to be available in any case. [See appendices]

As for the treatment process, trickling filter treatment method was selected which is one of the basic treatment and associated energy costs are lowest compared to advanced treatment plants (Goldstein & Smith, 2002). Agricultural water need was assumed that it did not require high quality of water. Table 23 shows energy costs of various wastewater systems.

Types of Treatment Facilities	Energy Consumption kWh/ac-ft
Trickling Filter	310
Activated Sludge	424
Advanced Treatment without Nitrification	489
Advanced Treatment with Nitrification	619

Table 23. Energy Use for Different Wastewater Systems (Source: Goldstein & Smith, 2002).

Since energy cost varies depending upon the plant size, a regression curve was developed based on given wastewater plant size in a paper named *"Energy-Water Nexus in Texas"* in order to calculate energy costs of the treatments (Stillwell, et al., 2009). Therefore, the energy requirement of treatment process can be developed based on the entered scenarios. The energy cost of the plant and treatment capacity are inversely proportional as illustrated in Figure 40.

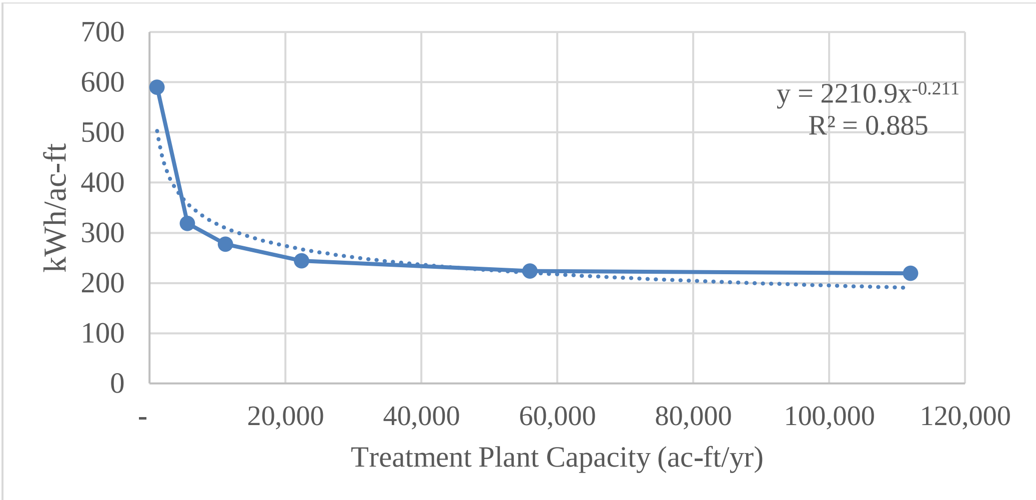

Figure 40. Energy Cost of Trickling Filter Water Plant. (Source: Stillwell et. Al)

Currently, there is no water conveyance system that can convey water from Houston to lands of Matagorda County. When applied, required energy and financial costs were taken into account for this study. It is important to note that this conveyance system consists of pipelines and pumps which can vary depending upon design system. While building larger pipelines, needed horsepower can be decreased and this reduces required pumps and energy costs. However, this would rise the cost amount since as long as pipe diameter rises, the unit price rises. Consequently, calculations of this study included an optimization in hydraulic calculations.

4.2.10.3 Lane City Reservoir

The LCRA's Lane City Reservoir is currently under construction and planned to be open for service in 2018 and will be located just north of the Wharton-Matagorda county line near Lane City in Wharton County. This reservoir will supply firm water for agricultural use, primarily, during the driest conditions while increasing the flexibility of managing releases of environmental flows into Matagorda Bay. Currently, there is no historic data available that can inspire future projections (LCRA, 2015). An assumption was made for the allocation of water from the lake to agriculture [see assumptions]. Even though the planned allocated water for agriculture of Matagorda County was not certain, LCRA is planning to allocate 22,727 ac-ft annual water for STP Nuclear Cooling according to the recent statewide water plan (TWDB, 2016a).

4.2.11 Irrigation Improvements

Technological improvements in agriculture for this study consist of the improvements in existing water conveyance system, which is known Gulf Coast Irrigation District, and applications of efficient on-farm irrigation systems. The information for improvement of conveyance system was used from TWDB recent report (TWDB, 2016a). As for existing on-farm irrigation systems, however, there is no available data referring to the situation of irrigation systems of Matagorda. Site observations helped assume 70% of total cropland as applicable field for on farm irrigation systems. After applying new irrigation systems, the efficiency of water use for farm was assumed to rise from 70% to 95% since LEPA irrigation system has 95% efficiency. Center pivot with half mile length was selected as new irrigation system. The installation cost including taxes of the state of Texas was $338 per acre land (Texas A&M Agrilife Extension, 2011).

4.2.11.1 Improvements on Conveyance System

LCRA's Gulf Coast Irrigation District which are mainly responsible for surface water conveyance in Matagorda County have planned to be improved periodically according to TWDB's recent water plan. The data for the cost of the irrigation conveyance improvements, totally $52,428,108 for Matagorda County, was taken from TWDB's 2016 Region K Water Plan (TWDB, 2016b). The conveyance loses of the system which depends on the water use were derived from a report regarding the seepage and loses in the Gulf Coast irrigation district published by LCRA (Bonaiti & Fipps, 2013).

4.2.11.2 Improvements On-Farm Irrigation System

There was no specific data available specifically on-farm for Matagorda. However, it was known that farmers in the county used to grow mainly rice and use furrow irrigation system. Therefore, more water-saver irrigation systems on farm were desired to be used as management strategy. Referencing Texas A&M Agrilife Extension's "Economics of Irrigation Systems" bulletin (Texas A&M Agrilife Extension, 2011), along with some assumptions [see assumptions], total cost for new on-farm irrigation systems were developed.

4.2.12 Groundwater depth

The formula for energy cost of groundwater pumping required the depth of water level. In this regard, to get an average number of the depth of groundwater, several well reports which were available via TWDB Water Data Interactive website, were utilized.

Consequent of reviewing 60 wells, 20ft average depth is determined and used for this study (TWDB, 2016i).

4.2.13 Food Production

Food Production refers to yield from croplands. Historical yield amounts showed that unit yield from the croplands had risen year by year because of several reasons such as genetic technology, better irrigation systems and management, and better fertilizer usage. Figure 41 below indicates us how the yield amounts have raised in Matagorda County since 1990. The annual data from USDA Surveys was used to make this graph (USDA - NASS, 2016a).

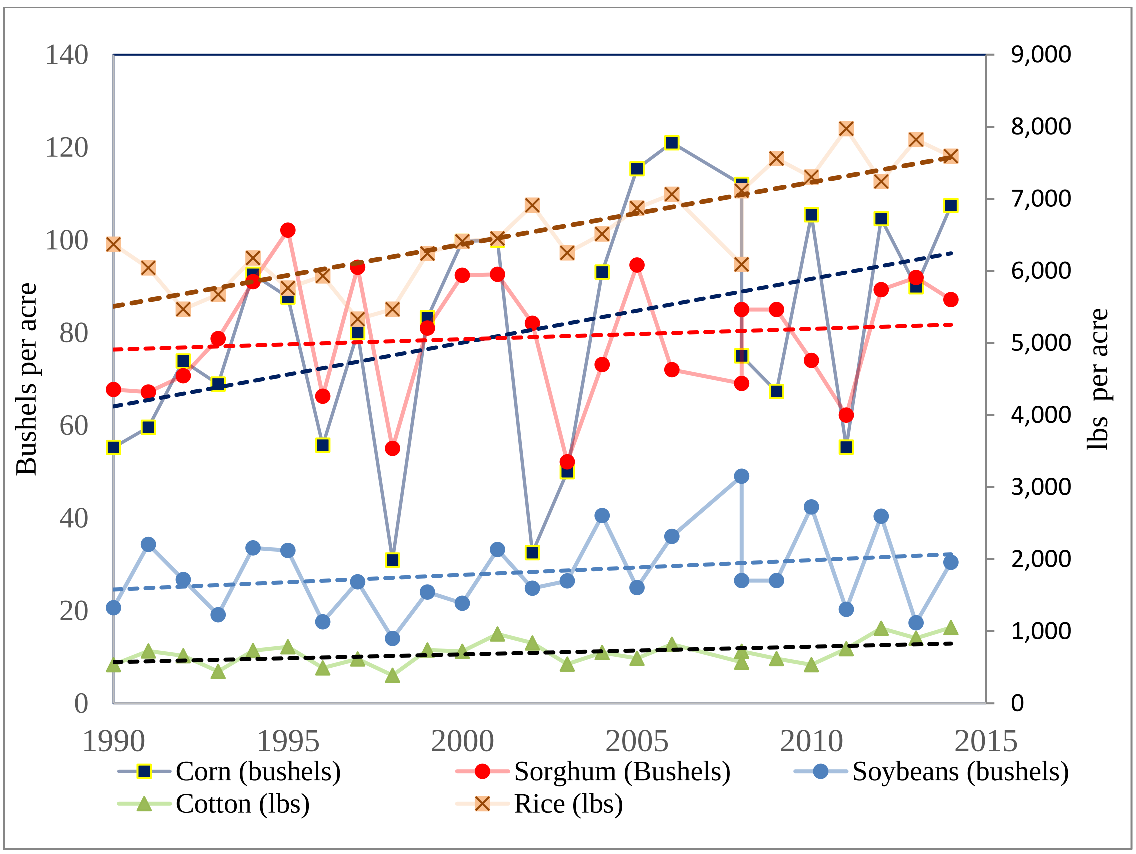

Figure 41. Historic Yields per Acre Land for Five Major Crops in Matagorda (Source: USDA Surveys)

Maximum yields of each crop were calculated using historical yield data from USDA's surveys and censuses (USDA - NASS, 2016a). Future has uncertainties which was one of the main challenges of the nexus analytics. The trend of the plots above while (a regulation applied) [see Methodology] provided yield per acre information for the future projections.

Yield amount for each crops depends on several parameters such as irrigation supply and scheduling, water quality, fertilizer, pest control, farming operations, manpower and so on. Some of the historic trends can be seen in Figure 41.

The tool was designed to be capable of giving variable inputs for food price and yield amount. However, the results of this study only include the trend values of the Table 24. After working on historical values, historic highest, lowest, mean, and trend values were presented. The year of 2070 was selected for the projection of trend values.

	Corn Bushels/acre	**Cotton lbs/acre**	**Rice lbs/acre**	**Sorghum Bushels/acre**	**Soybeans Bushels/acre**
High	121.0	1,052.0	7,970.0	102.1	49.0
Low	28.8	190.0	3,998.0	43.2	14.0
Median	73.7	597.7	5,963.8	74.3	25.7
Trend	175.9	1,442.6	12,472.3	94.8	48.9
Regulated trend	148.5	1,247.3	10,221.2	98.4	49.0

Table 24. Agricultural Yield Amounts per Acre Land (These Values can be Applied to Tool) (Source: USDA Surveys)

4.2.14 Food Revenue

Like unit yield from cropland as can be seen in Figure 41, the historical market prices of agricultural productions show upward trend with fluctuations as seen in Figure 42. Market values of Agricultural products as unit values were borrowed from historical values of each crops. USDA's historic statistics website for the state of Texas was utilized in this regard data (USDA - NASS, 2016b) [see appendices]. The US $ unit values since 1987 were evaluated and analyzed for the tool. (1-bushel sorghum is 56 lbs. (William, 1993))

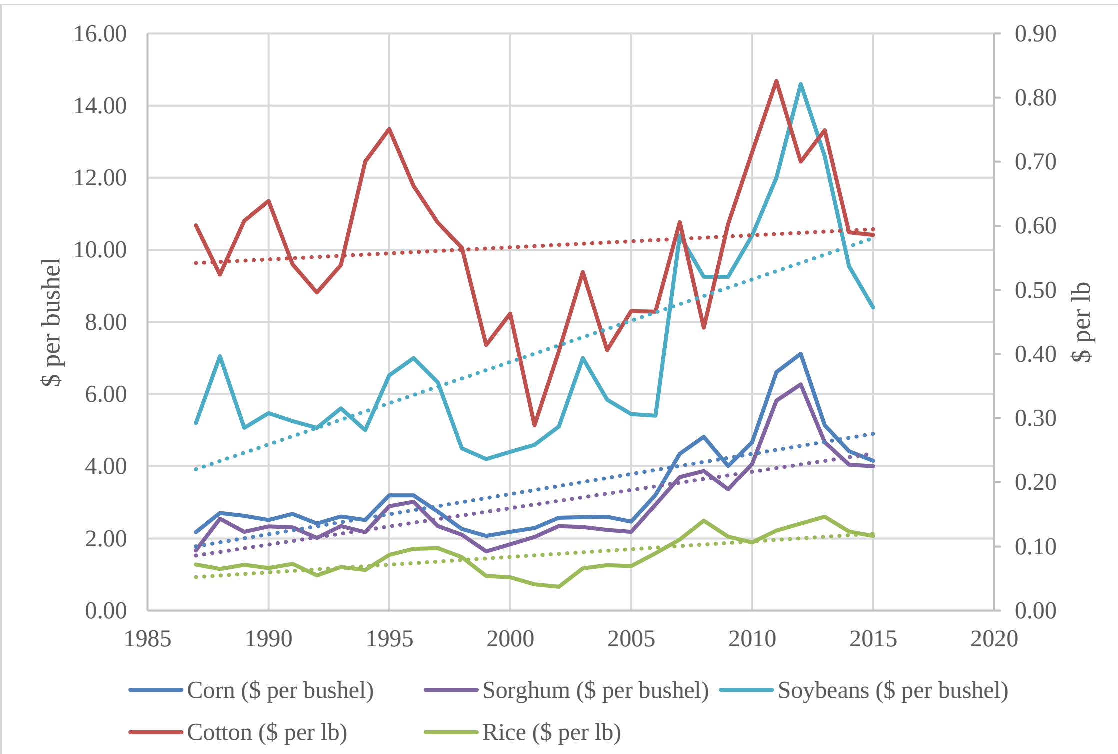

Figure 42. Historical Market Values of 5 Major Crops in Texas (Source: USDA Statistics)

The tool was capable to calculate the revenue from agricultural crops and livestock as described in methodology. Projection of crop and beef market for the year of 2070 was so multifaceted because many parameters such as oil prices, climate conditions, international economic markets, governmental policies could influence. At the meantime, historic values showed that unit food prices had been gradually rising (USDA - NASS, 2016b) [see appendices]. Considering the historic values of market prices, the assessment of values can be seen in Table 25.

Crop Market Price Options	Corn	Cotton	Rice	Sorghum	Soybean
	$ / bushel	$ / lbs	$ / lb	$ / bushel	$ / bushel
Historic Highest	7.12	0.83	0.15	6.27	14.6
Historic Lowest	2.07	0.29	0.04	1.64	4.2
Historic Medium	3.34	0.57	0.09	2.94	7.12
Linear Trend	11.03	0.7	0.18	12.46	22.91

Table 25. Market Prices of Agricultural Food Production Used in the Tool (Source: USDA Statistics)

The same procedure applied to agricultural food production was applied to livestock as well as presented in Table 26 (USDA - ERS, 2016).

Cattle Sold Market Price Options	Cattle $ / head
Historic Highest	1,959
Historic Lowest	768
Historic Medium	1,266
Linear Trend	4.868

Table 26. Market Prices of Cattle Used in the Tool (Source: USDA – ERS)

4.2.15 Carbon Footprint

The nexus model of Matagorda County included three types of energy: energy from diesel fuel, nuclear energy, solar energy. In terms of analytics, the amount of CO2 release depends upon two values: the amount of energy, and the energy resource [See methodology for calculations]. While EIA reports that CO_2 emission was 10.16 kg per diesel gallon (EIA, 2016a), a life cycle study by van Leeuwen and Smith demonstrates that the average CO_2 emission per kWh nuclear energy production was 115g per produced kWh (Leeuwen & Smith, 2012). Solar energy was assumed to have no carbon release.

4.2.16 Project Costs

In the analytics, all capital cost values were annualized. The value of discount rate value was assumed to be 3.125%, the value of 2016. In doing so, fifty-year life span period was selected.

4.2.17 Municipal Water Demand

Domestic water use including indoor and outdoor water use in Texas were borrowed from TWDB's historical water use estimate website [see appendices]. The year of the highest consumption of water per capita was 2011, and therefore it was selected to apply the data for future scenarios. The year of 2011, as stated before, was also the driest recorded year of the county. The water consumption per capita daily was 145.9 gallons (TWDB, 2016f). The data from TWDB states that the only source for domestic use was groundwater.

In this study, domestic water use is directly linked to population. Table 13 indicates the projected population values. Therefore, this study forecasted the number of people living in the year of 2070 as 44,815. Water consumption per capita daily was taken while looking at historical highest values shows is 145.9 gpcd including indoor and outdoor water use. This number is pretty much reflecting the average US domestic water use, which is 150 gpcd. Thus, total expected total water demand was calculated for the year of 2070.

4.2.18 Municipal Water Reuse

Building a treatment plant can be a solution to mitigate water stress and increase the sustainability of Matagorda. As for the municipal treatment plant, Advanced Wastewater Treatment (without Nutrification) type was selected since the plants produces enough quality of water. The energy cost for advanced treatment varies depending on the plant size. Basically, as long as the plant size rises, the energy cost per unit water decreases (Goldstein & Smith, 2002) (Stillwell, et al., 2009). Depending upon the plant size proposed in the scenario, the energy cost changes dynamically as can be seen in Figure 43.

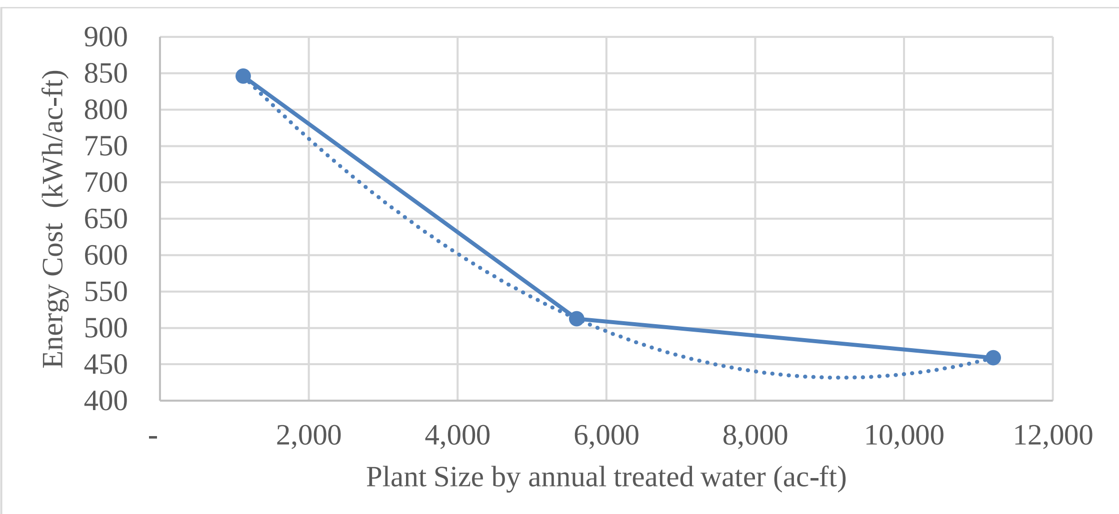

Figure 43. Advanced Wastewater Treatment Energy Consumption (Data Source: Goldstein &Smith)

In this study, building a treatment plant to reuse wastewater was considered intervention. The interventions of the amounts of municipal water reuse included 20%, 50%, and 80% of total municipal water consumption along with current practices that have no water reuse. Depending upon the applied interventions, water, energy, and cost parameters of scenarios were subject to change.

4.2.19 Industrial Water Demand

Water consumption of industrial water demand calculations had different methodologies. Industrial use was driven by companies exist in the county whereas municipal use by population. Historic Data from TWDB shows that industrial water consumers have used both surface water and groundwater resources. (TWDB, 2016f) [see appendices].

Industrial water demand was up to industrial activities occurring in the county. Industrial water demand was projected to be around 16,997 ac-ft in 2070 considering the historical trends. The portion of river water and groundwater contribution to water supply were assumed to remain same. Therefore, 12,059 ac-ft surface water and 4,937 ac-ft groundwater were determined for industrial for the year of 2070.

4.2.20 Industrial Water Reuse

Like municipal water use, industrial water was determined to be a possible intervention for mitigation of water stress facing in Matagorda County. The plant was designed to be Activated Sludge. Energy cost for desalination plant can be seen in the Figure 44 below.

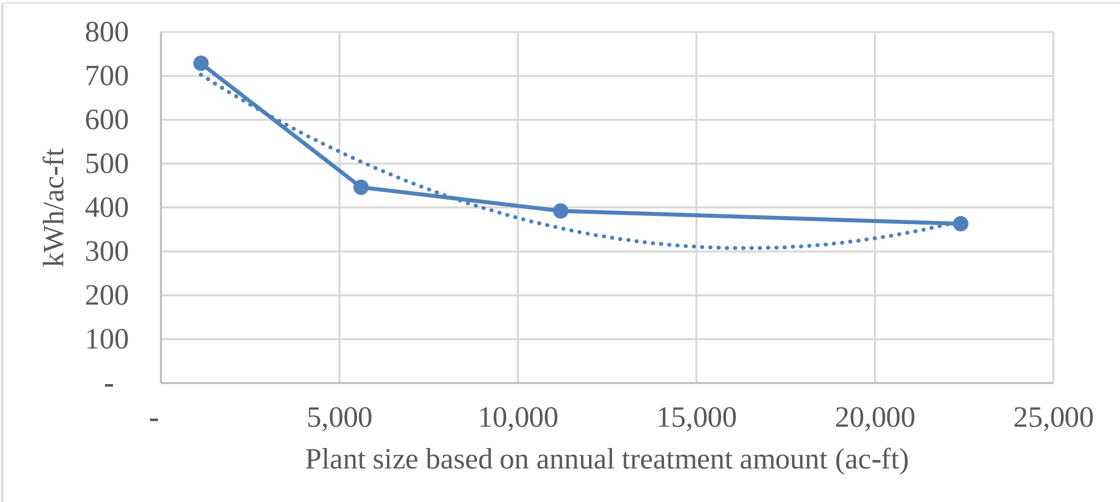

Figure 44. Energy Cost by Plant Size for Activated Sludge Wastewater Treatment (Data Source: Goldstein &Smith)

The capacity of the proposed plant for scenarios was various, which could be 20%, 50%, or 80% reuse of total industrial water consumption. Therefore, depending upon the applied interventions, water, energy, and cost parameters of scenarios were subject to change.

Energy demands for municipal and industrial water distribution were calculated based on the values in Table 27 below. The table comes from a report published by the Water Research Foundation & Electric Power Research Institute entitled "*Energy Use and Management in the Municipal Water Supply and Wastewater Industries*" (Pabi, et al., 2013)

Unit Process	Pumping Efficiency	Plant Production (ac-ft per year)			
		1,120	5,601	11,201	22,403
Raw water pumping, surface plant	High	118	589	1,177	2,355
	Medium	145	725	1,449	2,898
	Low	188	942	1,884	3,768
Raw water pumping, groundwater plant	High	750	3,748	7,496	14,992
	Medium	923	4,613	9,226	18,452
	Low	1,199	5,997	11,994	23,988
Finished water pumping	High	854	4,328	8,969	17,520
	Medium	1,040	5,327	11,038	21,563
	Low	1,352	6,925	14,350	28,032

Table 27. Water Pumping Intensity as a Function of Pumping Efficiency (kWh/day). (Adapted from a Report Entitled "Energy Use and Management in the Municipal Water Supply and Wastewater Industries" (Pabi, et al., 2013))

As seen from the table above, groundwater, surface water, and finished water were taken into account individually for the analytics of municipal and industrial water distribution. In the scenarios, while municipal users were using only fresh groundwater and its reuse (when applied), industrial users were using fresh surface water, fresh groundwater and their reuse (when applied).

4.2.21 Solar Energy Application

Solar Energy is currently becoming more popular on the world. Matagorda County is abundant in terms of solar power. This study considers solar energy application as an intervention to help reduce energy requirements of other interventions. The application of course will bring financial cost which would be analyzed.

National Renewable Energy Laboratory's (NREL) the System Advisor Model (SAM) providing most recent technologic performance and financial renewable energy production models was selected for this study to assess the solar power's contributions. SAM was publicly available for users such as project managers, engineers, policy analysts, and researchers (NREL, 2016). As for location and weather data, Palacios Municipal Airport's station was selected (ID = 722555). Only average weather data was available to use this model. Among available panels, one of the most efficient and widely used module, SunPower SPR-X22-475-COM, was selected. The efficiency of the module was 22.0395% and maximum power was counted as 476.495 Wdc. Other details is seen in Figure 45 below.

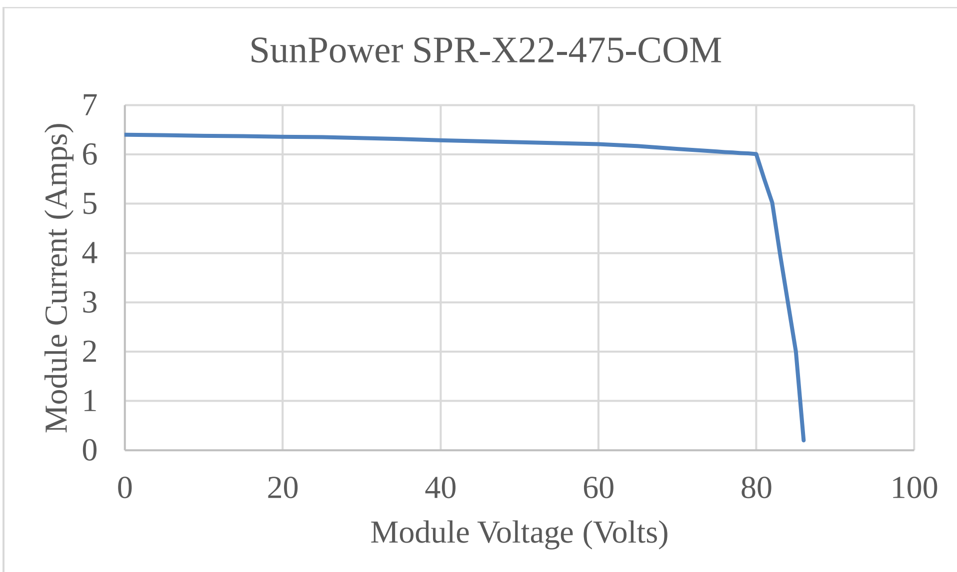

Figure 45. Module Characteristics of Selected Module. (Generated Using System Advisor Model (SAM) (NREL, 2016))

Inverters were designed based on various design of system and capacity. As a result of analytics and designs, the plot in Figure 46 was obtained and used to determine capital cost values of proposed installment when applied in a scenario.

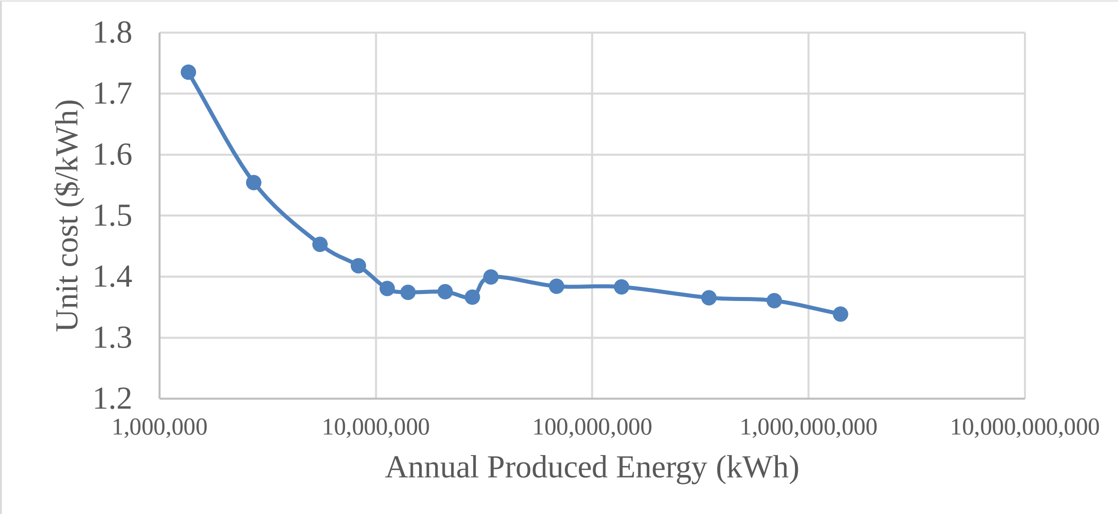

Figure 46. Unit Cost by Solar Farm Size (Adapted from System Advisor Model (SAM) (NREL, 2016))

4.2.22 Nuclear Energy Production of STP Nuclear Generation Plants

International Atomic Energy Agency (IAEA) provides information for each reactor found on the world. Data about nuclear net and gross energy production for STP's existing nuclear reactors were taken from IAEA. As for the proposed new reactors, they were borrowed from USNCR (IAEA, 2016) (USNCR, 2016a). Table 28 presents nuclear energy production amounts for each unit.

STP Reactor Units	Reactor Type	Net Capacity	Gross Capacity
Unit 1	Westinghouse 4-loop	1280 MW	1354 MW
Unit 2	Westinghouse 4-loop	1280 MW	1354 MW
Unit 3 (Planned)	ABWR	1350 MW	-
Unit 4 (Planned)	ABWR	1350 MW	-

Table 28. Nuclear Energy Production of STP Nuclear Generation Plant's Reactors (Sources: IAEA and USNCR)

4.2.23 Water Consumption and Environmental Data of STP Nuclear Plants

The application process of new reactors for STP included several environmental and water use information. Precise data regarding existing and proposed reactors were submitted while STPNOC during the application process of getting new licenses from USNCR. The final report entitled "*Environmental Impact Statement for Combined Licenses (COLs) for South Texas Project Electric Generating Station Units 3 and 4*" provides quite detailed data regarding the water consumption (USNCR , 2011). Some historical water use data were available from TWDB as well (TWDB, 2016f).

The annual data for lake surface evaporation was borrowed from TWDB. TWDB divides the state into several quadrangles to indicate accurate precipitation and lake evaporation data. The quadrangle number 912 was selected for annual evaporation rate of MCR calculations since 912 covers the plant area. The year from 1954 to 2015 with the annual highest lake evaporation was 2000. The annual evaporation was calculated and found as 71.73 inches' evaporation rate (TWDB, 2016g). Therefore, total annual evaporation as volume in harsh conditions was found as 41.483 ac-ft from MCR.

As stated before, 74,630 ac-ft water were presented for the evaporated water due to induction. Regular seepage occurs around 1,850 ac-ft and was expected to remain same in the future as MCR continues. The data was provided from STPNOC's reports (USNCR , 2011).

4.2.24 Alternative Cooling Systems and Water Resources

4.2.24.1 Extra Water from Lane City Reservoir

Lance city reservoir is currently under construction (LCRA, 2015). LCRA which is responsible for the construction of the reservoir did not declare precise data for the allocation of the reservoir. According to the recent statewide water plan, LCRA planned to allocate 22,727 ac-ft annual water for cooling of STP Nuclear Reactors (TWDB, 2016a). This number was utilized for the developed scenarios where Lane city reservoir was utilized.

4.2.24.2 Cooling Towers

Since there are no existing cooling towers in STP site, background information and data for cooling towers was referenced from those studies: *"Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature*" and *"Application of Dry Cooling in Nuclear Power Plants"* (Macknick, et al., 2012) (EPRI, 2008). As a result, contrary to what many people believe, the addition of cooling towers the plant actually increases the consumption of water. Thus, building extra cooling towers without using existing system was found environmentally and economically infeasible.

4.2.24.3 Once Through Sea Water Cooling Data

The study entitled "Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature" provided data for the calculation of water cooling requirements for once-through systems (Macknick, et al., 2012). Analytics showed that once through seawater without using the pond requires tremendous amount of water and energy. In fact, half of the energy produced by plant needed to be dedicated to the cooling system if applied. Thus, once through seawater cooling system was found environmentally and economically infeasible.

4.2.24.4 Seawater Cooling with Pond

The distance of MCR to the Gulf of Mexico for water withdrawal was taken from USNCR's Environmental Statement report (USNCR, 2016a). That was a1.5 mile.

4.2.24.5 Houston Reuse

City of Houston Water Conservation Plan provided the possible available wastewater data for the year of 2020 (City of Houston, 2014). None of the scenarios exceeded the limit of 200,000 ac-ft of wastewater.

4.2.25 Cost of Construction Values of Water Conveyance Systems

Cost of construction of pipelines, pump stations, pumps, water intake (from sea) buildings were calculated using TWDB's Unified Costing Model User's Guide that is prepared for regional water planning (HDR, Freese and Nicholes, 2013). The unit prices were listed in appendices.

4.2.26 Bringing Historical Construction Cost Values to Today

In this study, for pipeline, pump, and pumping stations, bringing historical construction cost estimate data to the present was accomplished through the use of the Engineering News Report Construction Cost Index (ENR CCI). This value is updated on a very regular basis. Also, USDA Natural Resource Conservation Service's annual construction indexes were utilized when needed (USDA - NRCS, 2016a). The most recent ENR CCI value available was 10181.92, updated in February 2016. The CCI value has been increasing since 1913 when the value was 100. In order to compare with past values a multiplication factor was developed to bring the costs equal to the present. For example, the 2000 CCI value was 6221. In order to being 2000 cost estimate values to be viable in 2016, the 2000 costs were multiplied by 1.636701.

As for bringing historical construction values of construction cost of treatment and desalination plants, USBR's Cost Trends were applied. Considering the most recent available construction indexes, April values of 2016 was selected (USBR, 2016).

4.2.27 Discount Rate

The discount rate used in the annual cost analyses of the various interventions was the water resources projects discount rate for 2016, 3.125%. This discount rate was selected in order to limit the number of variables between scenarios and to keep the same analysis consistent across all projects. This discount rate is updated each October by the USDA NRCS to be applied nationwide (USDA - NRCS, 2016b).

4.3 Assumptions

Even though the data analysis was inclusively studied as seen in the previous titles, some assumptions needed to be made when required. Those assumptions can be seen in the list below:

- ✓ The latitude of the city of Palacios, 28.7 N, and average 3m county-wide average altitude were selected for the calculation of crop water requirements using FAO's radiation method.
- ✓ It was assumed that farmers of Matagorda use 10% of more water due to irrigation scheduling and management practices in the United States.
- ✓ Green water was defined as water from precipitation to soil that leaves the soil via evaporation. 75% of precipitation was assumed to go back to hydrologic cycle via evaporation as green water while the rest can be either run-off or infiltrated.
- ✓ Considering the lack of data in current irrigation practices and on-farm systems, it was assumed that 30% of total agricultural land was not available for the improvement. The average irrigation efficiency of existing irrigation system was assumed as 70%. The new irrigation system applied as a new technology had 95% efficiency.
- ✓ One assumption for fresh groundwater was that there was no need to treat fresh groundwater for any purposes including municipal, agricultural, industrial, and cooling. The available brackish groundwater was assumed to be 100,000 ac-ft if needed

- ✓ LCRA did not share precise data for the future water allocation of the Lane City Reservoir which is still under construction. It was assumed that farmers in Matagorda will have 35,000 ac-ft of total 100,000 ac-ft expected annual water supply.
- ✓ Since Gulf Coast Aquifer Irrigation District had already an existing irrigation conveyance system and infrastructure, it was assumed that there is no financial and energy cost for agricultural water use of the Lane City Reservoir.
- ✓ Transport type used for produced yield's transportation were not certain in Matagorda because railroad, highway, aviation, and even seaway could be used for food transportation. Further challenge was on the distances of food transportation. While some food was consumed in the county, some other could be conveyed national or international spots. Considering all the complexities and uncertainties, transportation of food and their energy cost was not included.
- ✓ Beside water intake by animals, 20% of total water intake requirement was estimated for waste of water in ranches and other requirements as shower in hot summers.
- ✓ Calculations for livestock was revolved around water and food but not energy since there was no direct data available for energy use of cattle. Namely, the energy consumption of livestock was neglected.
- ✓ Even though aquaculture is playing an essential role in the economy of Matagorda County, it was not taken into account because of lack of data and the gap in the literature in terms of WEF nexus interlinkages of aquaculture.

- ✓ Large amounts of wastewater were available from the city of Houston. This study suggested that wastewater could be used for agricultural water resources and cooling for STP. Some wastewater was directly treated in Houston. Wastewater processing, financial and energy costs, were not included to this study due to the lack of wastewater data. Instead, wastewater was directly transferred from Houston to Matagorda using pipelines and pumps. The distance between Houston and Matagorda to construct pipelines was defined as 50 miles. Elevation difference was assumed at 100ft considering variable earth surfaces. While calculating pipeline cost values, it was assumed that 67% of distance where pipelines constructed was in rural areas and 33% in urban.
- ✓ Water treatment of municipal and industrial wastewater was considered separately. After treatment, reuse water was applied to the original consumers.
- ✓ The unstable future of fossil fuels considering the 50-year lifespan of the study, historic fluctuations in production, absence of produced water data, controversies about offshore platforms, and uncertainties of future projections caused not to take oil & gas production into account.

5. RESULTS AND DISCUSSIONS

Results are presented in two phases: analytic outputs of each of the scenario and outcomes which indicate the rankings of the scenarios based on various perspectives. Discussions follow the results to disambiguate.

5.1 Outputs from the Tool

The WEF nexus analytic tool provided quantitative outputs for the scenarios which can further be analyzed to recommend the most sustainable scenarios. The tool is able to provide various kind of outputs for each of the scenario as stated. The following graphs show the analytic results obtained from the tool. In the following graphs, x axes represent the scenarios while y-axes are for output records.

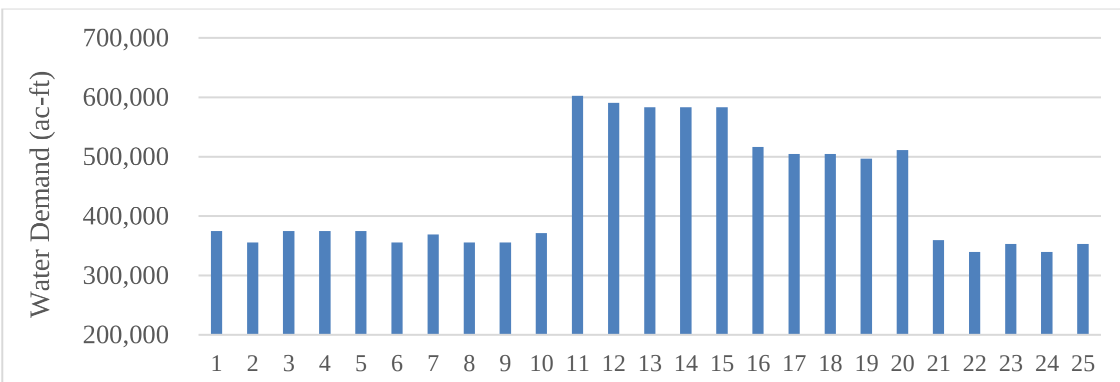

Figure 47. Water Demand

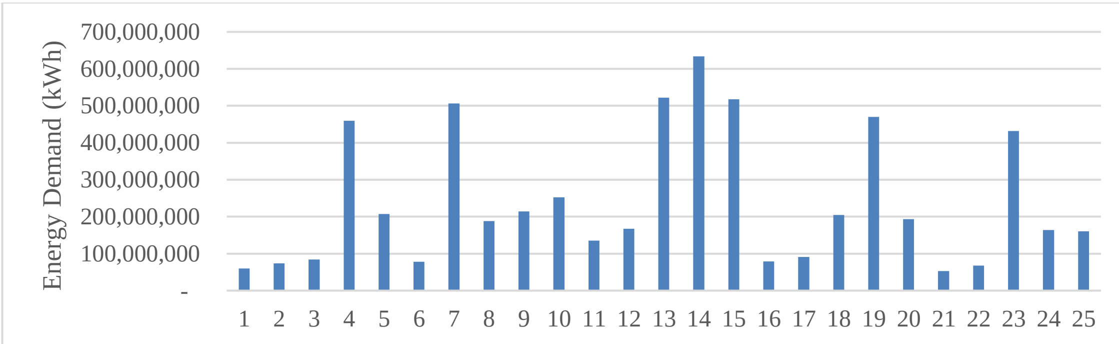

Figure 48. Energy Demand

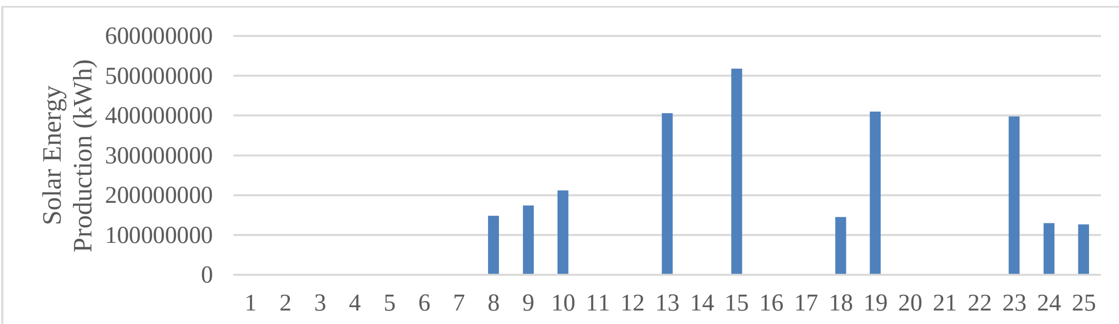

Figure 49. Solar Energy Production Amounts

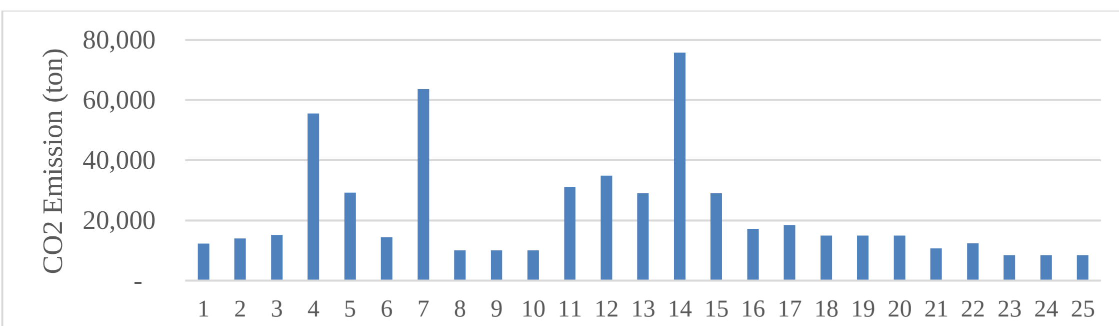

Figure 50. CO2 Emission

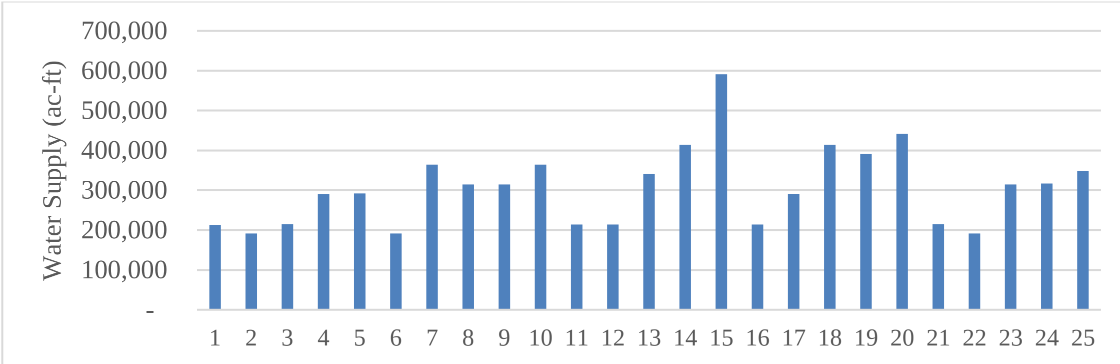

Figure 51. Water Supply

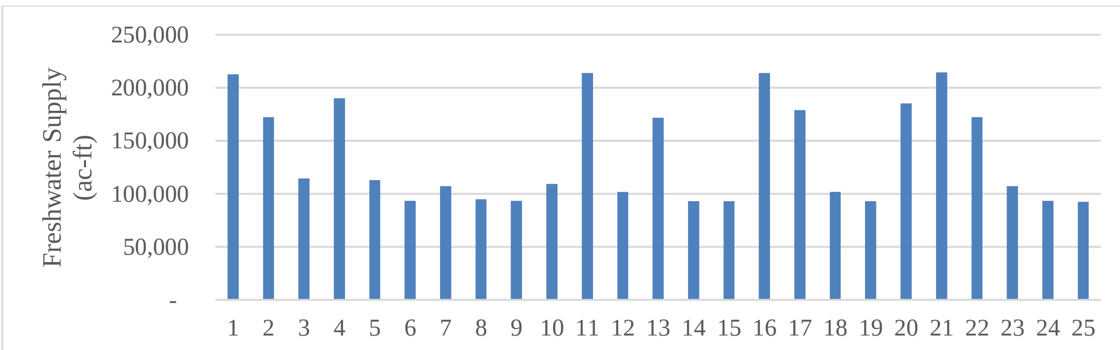

Figure 52. Freshwater Supply

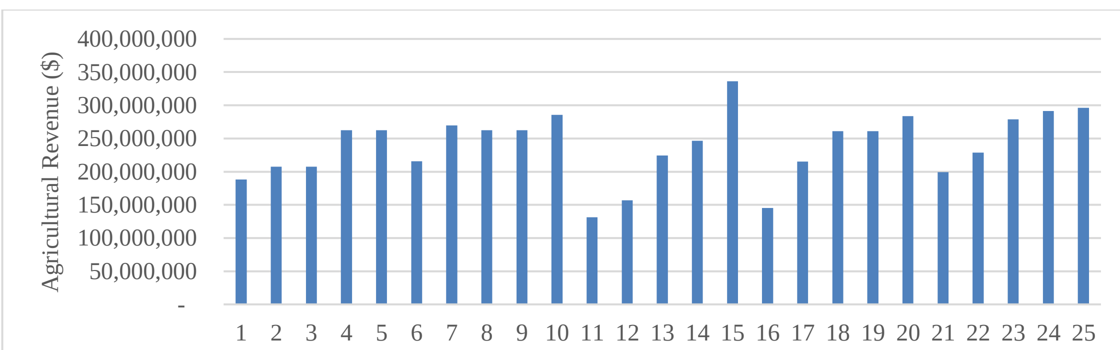

Figure 53. Agricultural Revenue

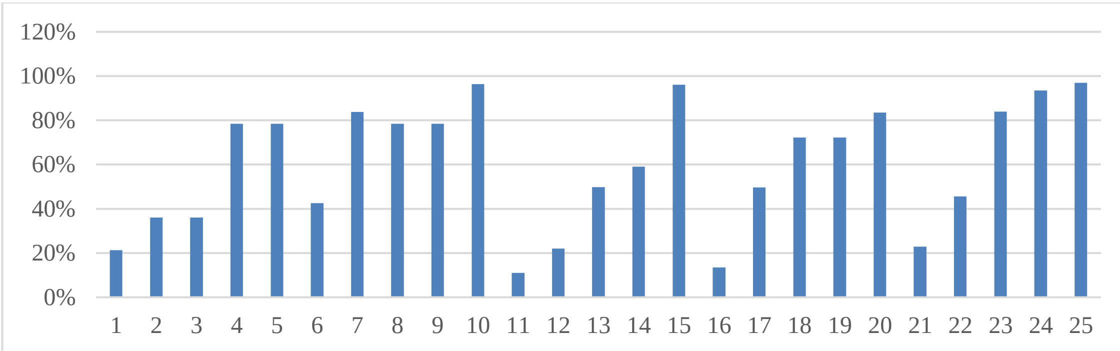

Figure 54. Irrigation Supply Percentage

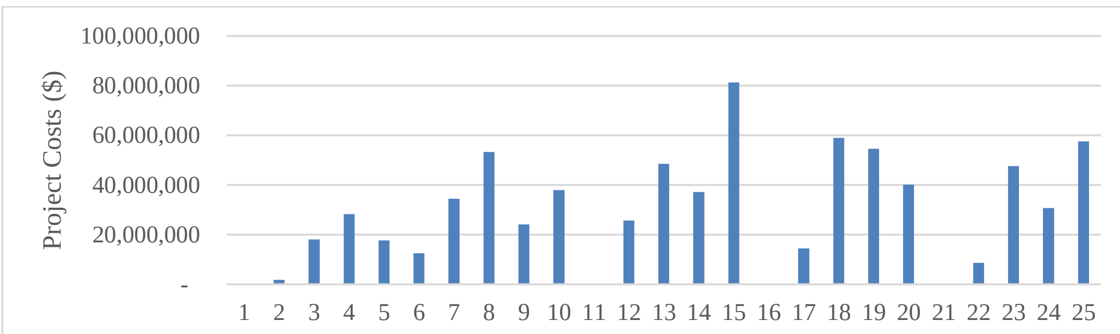

Figure 55. Project Costs

As can be seen from the Figure 47-55 above, several outputs which have various units became available for each scenario. Some of the outputs which have a wide spectrum of reflectance of the Water-Energy-Food nexus were selected and analyzed to draw recommendations. Preferred weighting factors were applied to reflect the perspectives of stakeholders or observers.

5.2 Weighting Factors

As described in the methodology, the preferred weights can be seen Table 12 in the chapter of Methodology.

5.3 Outcomes

Outcomes of the study are the rankings of the scenarios based on sustainability analyses. Scenarios were ranked based on water-centric, energy-centric, food-centic, cost-centric, environment-centric, all-equal (overall) perspectives. The results were presented in Figure 56-61 below. The x axes represent the scenarios while y axes represent sustainability indexes.

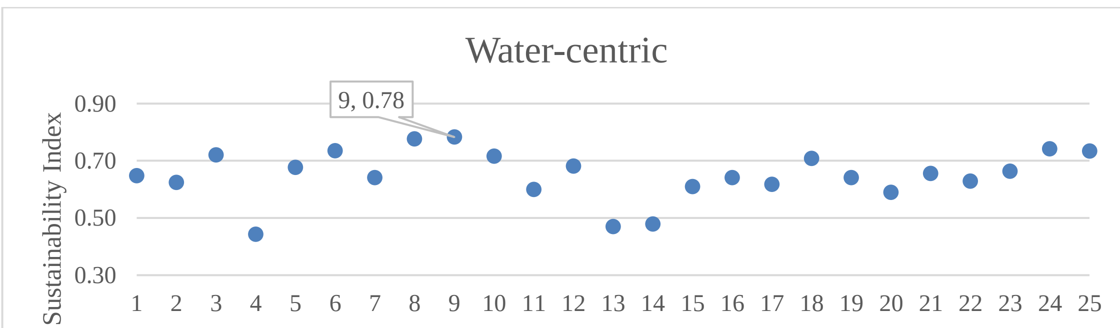

Figure 56. Outcomes of Water-Centric Analysis

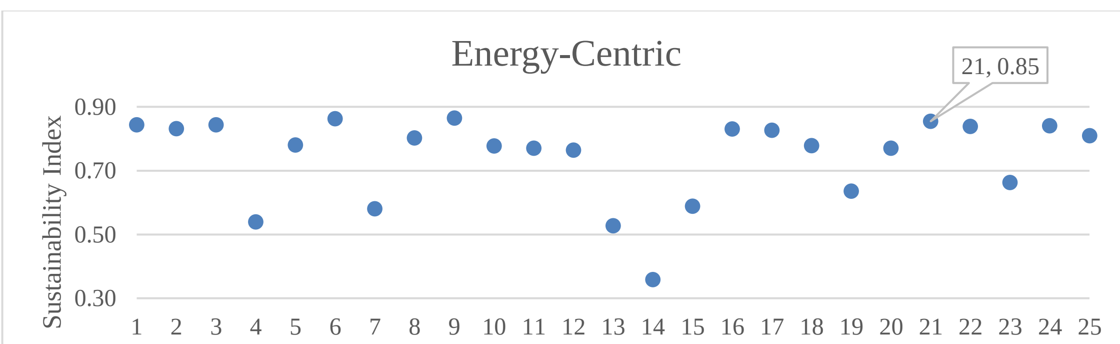

Figure 57. Outcomes of Energy-Centric Analysis

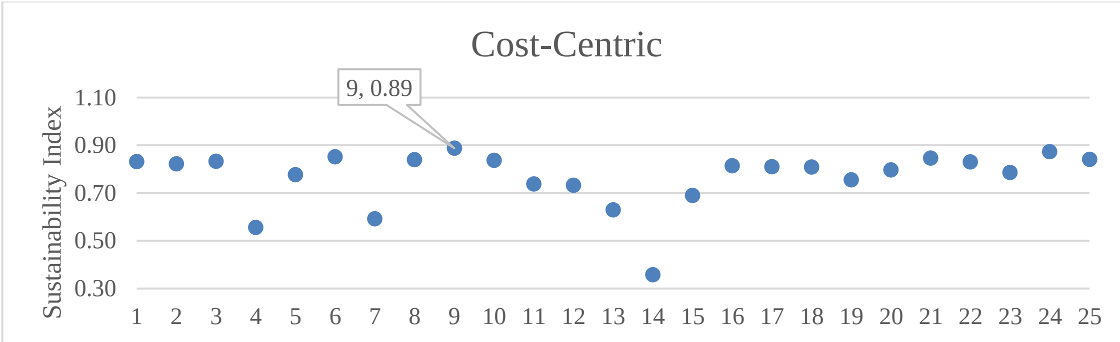

Figure 58. Outcomes of Cost-Centric Analysis

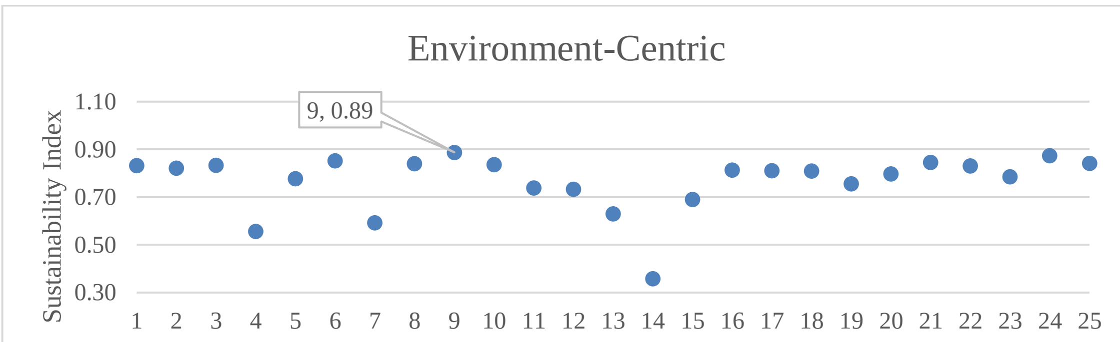

Figure 59. Outcomes of Environment-Centric Analysis

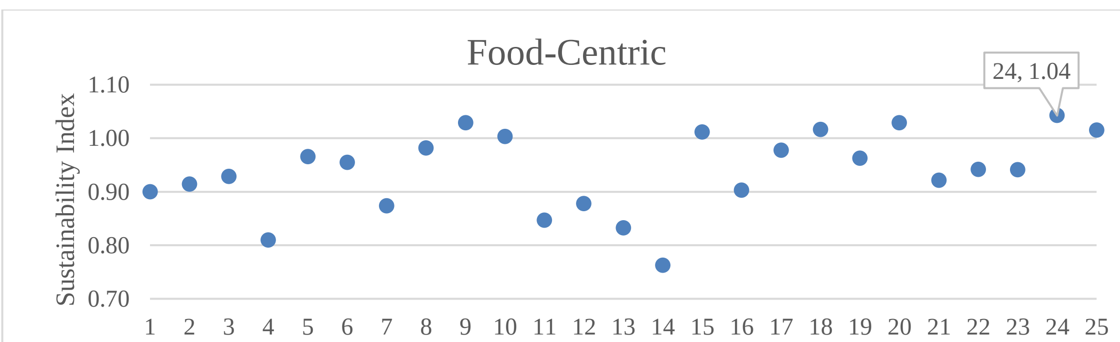

Figure 60. Outcomes of Food-Centric Analysis

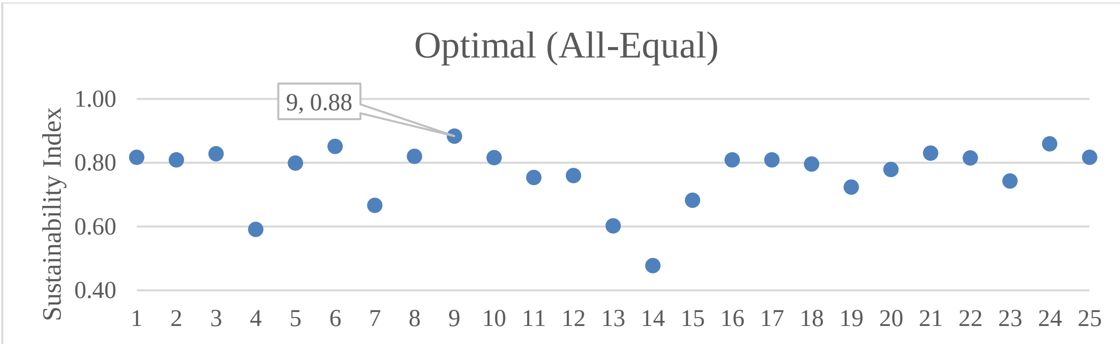

Figure 61. Outcomes of Optimal (All-Equal) Analysis

5.4 Evaluations of the Results

When all parameters equally considered, Scenario-9 is ranked the first. Scenario-9, as can be seen from scenarios Figure 36. Scenarios and Possible Interventions Embedded in the Scenarios, includes current land allocation and crop pattern, irrigation improvement applications, water supply from the new reservoir and brackish groundwater, 80% water reuse for both municipal and industrial water use, altering cooling water from river water to seawater, and solar farm installation. As for the least sustainable scenario, scenario-14 comes forefront. As differences between scenario-9 and scenario-14 [the most and least sustainable scenarios], it can be clearly seen that scenario-9 has more agricultural land for cultivation which demands more water, water supply from seawater through seawater, no water reuse for industrial use and no solar farm. First scenario is a base scenario which has no intervention. Scenario 1 is considered base scenario (Business as usual).

In order to validate the results of sustainability analysis, outputs from the tool were reviewed. Table 29. Outputs of Best And Worst Sustainable Scenario Along With Base below indicates the outputs of different parameters of the base, best, and worst scenarios with regard to sustainability.

	Base Scenario 1	Best Scenario 9	Worst Scenario 14
Water Demand (ac-ft)	374,874	355,419	583,628
Water Supply (ac-ft)	212,843	299,520	549,279
Energy Demand (kWh)	59,458,409	144,334,764	754,143,733
Solar Energy Production (kWh)	0	103,990,216	0
CO2 Emission (ton)	12,284	10,086	102,397
Ag. Revenue ($)	188,218,475	239,187,955	270,599,514
Project Costs ($)	190,772	19,159,627	57,765,111
Ag. Supply percentage	21%	61%	57%

Table 29. Outputs of Best And Worst Sustainable Scenario Along With Base

In this regard, water demand of the county is 374.874 ac-ft for scenario-1 (base scenario), while it is 355,419 ac-ft for scenario-9 (most sustainable). As for worst sustainable scenario, scenario-14, 583,628 ac-ft water is demanded. It is desired for a scenario to have less water demand as the outcomes show scenario-9 has less demand.

When it comes to water supply, scenario-14 provides highest water supply. Then, scenario-9 and scenario-1 are ranked respectively. It is expected to have more supply to be sustainable but it is also important to note that water supply values are not for only fresh water supplies. Figure 62 shows the sources of water supply. Similar records could be seen for other parameters as well as water as seen in the values below. Each water supply source has different energy footprint, which cause tremendously different energy demands.

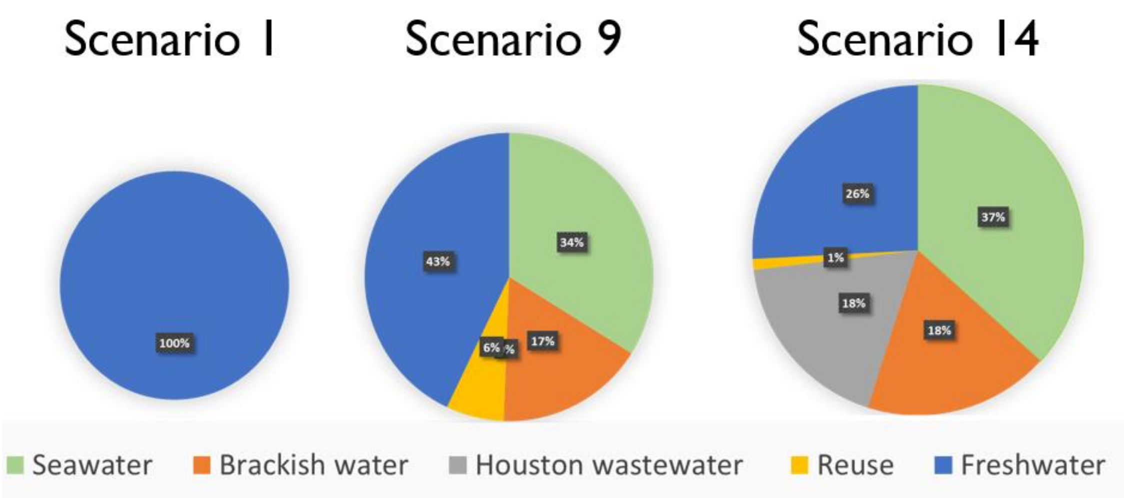

Figure 62. Water Supply Sources

When the energy demands are examined, the highest demand value can be seen on the scenario-14 which is around 13 times higher than base scenario, with more than 750 million kWh. The energy demand of scenari-14 clearly shows one of the reasons why the scenario is evaluated worst sustainable scenario. When the base (scenario-1) and the best (scenario-9) scenario are compared, it can be seen that scenario-9 has higher energy demand. However, the gap can be fulfilled by solar energy production [see Table 29].

Comparisons of CO_2 emission of the scenarios above shows that the less detrimental scenario-9 is the best scenario, which is little less than scenario-1.

As for the financial analysis, scenario-9 (the most sustainable scenario) provides approximately annual $22 million more revenue than scenario-1 (Business as usual) when project costs considered. Even though the outputs of scenario-14 illustrate scenario-14 seems to propose a little bit more revenue, the project cost values and other parameters such as energy demand makes scenario-14 less advisable.

Overall, the outcomes of the study should be reviewed while considering the outputs of each scenario to evaluate the results. The outputs of each scenario as can be seen in Figures 47-55. Project Costs illustrate how much the outcomes of the study are advisable. Therefore, the outcomes can be validated while approaching holistically.

5.5 Discussions

This study prioritizes water security while considering food and energy interlinkages. The outcomes of the study indicate that scenario-9 is the best scenario in terms of water sustainability. Also, from the perspectives of environment, cost, and all-equal, scenario-9 is ranked first. As for the energy perspective, one of the main pillars of this study, scenario-21 ranks the most sustainable scenario [see Figure 57. Outcomes of Energy-Centric Analysis]. From the food perspective, the study shows that scenario-24 is the most sustainable scenario [Figure 60. Outcomes of Food-Centric Analysis]. Therefore, this study asserts different advisable scenarios for various stakeholders or observers exist in Matagorda County case.

6. CONCLUSIONS

Achieving the most sustainable water allocation requires multi-dimensional analysis since primary resources are inextricably linked. Also, various perspectives from stakeholders and observers should be considered. The WEF nexus approach built in this study helped analyze various angles of interventions and produce advisable scenarios for stakeholders, observers and policy makers. Matagorda County was well-suited for a case study for the water energy- food nexus due to its current and projected water shortages, high water demands for electric power production and agricultural use.

The study demonstrated that the WEF nexus approach built in this study helps select most sustainable combinations of possible water-related infrastructure. If the outcomes of the study are applied, agricultural sector, which has been suffering from lack of water for many years, will make more benefit and be more productive than usual. Prosperous agricultural commerce is expected to strengthen other sectors as well since the considerable amount of the population is depended on the agriculture sector in the county. More importantly, improving economic well-being will be provided while reducing the consumption of natural resources and not sacrificing existing industrial activities including energy production in Matagorda County.

Further contributions to the WEF nexus platform built in the study such as adding environmental responses to possible interventions, applying more coherent data, considering stakeholder behavior (willingness to apply recommendations) would increase the validity and accuracy of results presented in the paper.

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APPENDIX A

A-1: Matagorda County Active Surface Water Rights

WR Seq	WR Issue Date	Owner Name	Owner Type Code	Div. Amnt Value (ac)	UseCode
1	6/3/1988	OXEA CORP	2	3,222	2
1	2/7/1985	JOHN S RUNNELLS III	1	17	3
2	2/7/1985	TIMOTHY R BLAYLOCK ET UX	3	26	3
1	2/7/1985	BEN H TOWLER JR	1	6	3
2	2/7/1985	MICHAEL D STONE	1	24	3
1	2/7/1985	ESTATE OF P J REEVES JR	5	20	3
1	2/7/1985	D R ALFORD	2	40	3
1	2/7/1985	HUDGINS DIVISION OF HD HUDGINS	1	800	3
1	2/7/1985	MICHAEL J PRUETT	1	44	3
2	2/7/1985	SAMANTHA ANNETTE HUDGINS	1	41	3
1	2/7/1985	JOHNNY WAYNE & VICKI L JONES	1	2	3
2	2/7/1985	JOHNNY WAYNE & VICKI L JONES	1	78	3
1	2/7/1985	DONALD R & JANICE M KOPNICKY	1	30	3
1	2/7/1985	JOHN A HUEBNER JR ET AL	4	550	3
2	2/7/1985	JOHN A HUEBNER JR ET AL	4	250	3
1	2/7/1985	RUSSELL & JUANITA MATTHES	1	880	3
1	2/7/1985	FRANCIS I SAVAGE	1	411	3
2	2/7/1985	O B STANLEY	1	2,339	3
1	2/7/1985	E CROSS CATTLE CO INC	2	668	3
2	2/7/1985	E CROSS CATTLE CO INC	2	600	3
1	2/7/1985	E CROSS CATTLE CO INC	2	592	3
1	3/5/1981	LILLIAN G ZERNICEK	1	80	3
1	2/16/1982	LINDA C MOORE	1	90	3
1	9/14/1982	THE MINZE LAND INVESTMENTS LP	2	1,000	3
1	4/4/1983	FUTURO FARMS INC	2	450	3
2	4/4/1983	G P HARDY III	1	-	3

Continued

1	4/29/1983	BETTY GENE MCAFERTY ET AL	4	35	3
1	4/29/1983	JOHN SCHMERMUND	1	1,500	3
1	6/24/1983	RUNNELS PASTURE COMPANY LTD	2	219	3
1	6/20/1984	JULIA HOLUB ET AL	4	25	3
1	4/29/1985	DON A CULWELL ET AL	4	750	2
2	4/29/1985	DON A CULWELL ET AL	4	1,500	2
3	4/29/1985	DON A CULWELL ET AL	4	-	7
1	1/20/1987	MAX CORNELIUS JOHNSON ET AL	4	400	3
1	1/20/1987	LAWRENCE J PETERSEN ET UX	3	400	3
1	1/20/1987	TRES CREEK LLC	2	120	3
1	1/20/1987	LOUIS F HARPER	1	301	3
1	1/20/1987	ARTHUR A PRIESMEYER	1	93	3
1	1/20/1987	TRES CREEK LLC	2	20,615	3
1	1/20/1987	MRS GLEN HUTSON ET AL	4	7	3
1	1/20/1987	SOUTH TEXAS LAND LTD PARTNER	2	1,500	3
1	12/23/1986	MATAGORDA BAY AQUACULTURE INC	2	316	2
1	8/26/1988	WYLIE VENTURES, LLC	2	1,443	3
1	6/28/1989	STP NUCLEAR OPERATING COMPANY AGENT	2	-	2
2	6/28/1989	STP NUCLEAR OPERATING COMPANY AGENT ETAL	4	102,000	2
3	6/28/1989	NRG TEXAS LP	2	-	2
1	2/22/1993	MATAGORDA CO DRAINAGE DISTRICT 1	2	260	8
1	6/28/1989	LOWER COLORADO RIVER AUTHORITY	2	262,500	3
2	6/28/1989	LOWER COLORADO RIVER AUTHORITY	2	-	1
3	6/28/1989	LOWER COLORADO RIVER AUTHORITY	2	-	2
4	6/28/1989	LOWER COLORADO RIVER AUTHORITY	2	-	4
1	6/5/1998	TEXAS BRINE CO LLC	2	-	2
1	4/25/2001	HERFF CORNELIUS	1	2,400	3
2	4/25/2001	HERFF CORNELIUS	1	-	2

Owner Type Code	Use Code
1 = Individual	1 = Municipal/Domestic
2 = Organization	2 = Industrial
3 = Et Ux	3 = Irrigation
4 = Et Al	4 = Mining
5 = Estate or Trust	5 = Hydroelectric
6 = Et Vir	6 = Navigation
7 = Individual Unverified	7 = Recreation
8 = Organization Unverified	8 = Other
9 = Estate or Trust Unverified	9 = Recharge
10 = Archive	11 = Domestic & Livestock Only
11 = Et Ux Unverified	13 = Storage
12 = Et Al Unverified	

WR Sec indicates water-right sequence number

A-2: Estimated Diesel Requirements for Farming Operations Of Crops

Estimated Fuel Requirements For Selected Farming Operations *(Extension Engineering - Handbook - The University of Georgia College of Agricultural and Environmental Sciences Cooperative Extension)*			
	Diesel, Gallons Per Acre		
	Low	Average	High
TILLAGE OPERATIONS:			
Moldboard plow	0.95	1.9	3.8
Chisel plow	0.6	1.15	2.35
Heavy tandem disk	0.4	0.8	1.6
Standard tandem disk			
plowed soil, first time	0.35	0.65	1.3
plowed soil, second	0.25	0.5	1
corn stalks, etc.	0.3	0.6	1.15
Spring-tooth harrow	0.2	0.45	0.9
Spike-tooth harrow	0.15	0.3	0.6
Field cultivator	0.35	0.75	1.45
PLANTING OPERATIONS:	0.35	0.5	0.75
Row-crop planter (with fertilizer, etc.)	0.25	0.35	0.55
Grain drill	0.9	1.3	1.95
Transplanter			
CROP CULTIVATION:			
Row crops, first cultivation	0.3	0.45	0.65
Row crops, second cultivation	0.25	0.35	0.55
Rotary hoe	0.1	0.2	0.3
HARVESTING OPERATIONS:			
Cutterbar mower	0.3	0.45	0.65
Mower-conditioner (pto)	0.45	0.75	1.1
Mower-conditioner (self-propelled)	0.7	1	1.55
Hay rake	0.15	0.2	0.35
Baler, hay	0.7	1	1.55
Forage harvester	1.65	2.5	3.7
Combine harvester			
small grain	0.75	1.1	1.65
soybeans	0.8	1.2	1.8
corn	0.9	1.3	1.95
Corn picker	0.6	0.95	1.4
Continued			
Picker-sheller and Picker grinder	0.75	1.1	1.65

Potato harvester	1.05	1.6	2.4
Vegetable harvester	1.15	1.75	2.65
Tree fruit harvester (shaker)	1.95	2.9	4.4
MISCELLANEOUS OPERATIONS:			
Row crop sprayer (each operation)	0.08	0.1	0.2
Orchard sprayer (each operation)	0.35	0.55	0.85
Stalk shredder	0.45	0.65	1
Fertilizer spreader (bulk, spinner)	0.1	0.15	0.2
Anhydrous ammonia applicator	0.95	1.15	1.7
Forage blower (haylage or corn silage)	0.7	1	1.55

A-3: Historic Annual Total Treated Wastewater in Houston

Months	2013 Total Treated Wastewater ac-ft/year (Adapted from Water Conservation Plan - Effective September 2014 through May 2019)
January	19,949
February	16,798
March	17,397
April	20,973
May	20,811
June	19,161
July	20,393
August	20,456
September	21,703
October	24,888
November	22,408
December	20,115
Total	245,000

1 ac-ft is 325,851 gallons. Therefore, for the year of approximately 245,000 ac-ft wastewater was treated in Houston in 2013. Less than 185 ac-ft was used as reuse.

A-4: Historical Market Values of Studied Crops in Texas

Year	Corn ($ per bushel)	Cotton ($ per lbs)	Rice ($ per cwt)	Sorghum ($ per cwt)	Soybeans ($ per bushel)
2015	4.15	0.59	13.00	7.15	8.40
2014	4.42	0.59	13.80	7.23	9.55
2013	5.14	0.75	16.40	8.33	12.60
2012	7.12	0.70	15.20	11.20	14.60
2011	6.61	0.83	14.00	10.40	12.00
2010	4.67	0.71*	11.90	7.26	10.40
2009	4.01	0.60	12.90	6.00	9.25
2008	4.82	0.44	15.70	6.91	9.25
2007	4.35	0.61	12.40	6.60	10.40
2006	3.20	0.47	10.00	5.24	5.40
2005	2.47	0.47	7.77	3.89	5.45
2004	2.60	0.41	7.96	3.99	5.85
2003	2.59	0.53	7.35	4.13	7.00
2002	2.57	0.40	4.16	4.18	5.10
2001	2.29	0.29	4.61	3.64	4.60
2000	2.18	0.46	5.82	3.28	4.40
1999	2.07	0.41	6.04	2.93	4.20
1998	2.26	0.57	9.32	3.76	4.50
1997	2.74	0.61	10.90	4.18	6.33
1996	3.19	0.66	10.80	5.39	7.00
1995	3.19	0.75	9.73	5.17	6.52
1994	2.51	0.70	7.12	3.88	5.00
1993	2.61	0.54	7.60	4.18	5.61
1992	2.41	0.50	6.17	3.60	5.07
1991	2.68	0.54	8.15	4.12	5.25
1990	2.51	0.64	7.41	4.16	5.47
1989	2.63	0.61	8.02	3.89	5.07
1988	2.71	0.52	7.24	4.55	7.05
1987	2.17	0.60	8.07	2.98	5.20

*: missing data-averaged looking at previous and the following years

A-5: Historical Annual Yield Produced by Unit Land in Texas

Years	Corn (bushel per acre)	Cotton (pounds per acre)	Rice (pounds per acre)	Sorghum (bushel per acre)	Soybeans (bushel per acre)
2015	135	614	6,900	61	26
2014	148	645	7,360	61	38.5
2013	136	646	7,740	56	25.5
2012	129	632	8,370	59	26
2011	91	592	7,190	48	19
2010	144	704	7,160	70	30
2009	124	635	7,770	48	25.5
2008	118	659	6,900	52	24.5
2007	148	843	6,550	65	37.5
2006	121	679	7,170	48	24
2005	114	724	6,600	60	26
2004	139	695	6,840	62	32
2003	118	480	6,600	54	29
2002	113	540	7,100	51	28
2001	118	483	6,850	50	26
2000	124	432	6,700	61	27
1999	129	477	5,900	63	27
1998	100	526	5,600	46	22
1997	138	477	5,500	59	28
1996	112	511	6,200	48	26
1995	114	375	5,600	54	25
1994	117	461	6,000	59	33.5
1993	115	486	5,400	57	19
1992	125	445	5,800	62	33
1991	110	419	6,000	61	31
1990	90	479	6,000	52	25
1989	106	376	5,700	53	30
1988	96	475	6,000	63	28
1987	107	508	5,900	63	28
1986	112	356	6,250	57	23
1985	105	406	5,490	59	25
1984	93	377	4,940	53	29
1983	97	324	4,340	50	22.5
1982	105	303	4,690	55	25
1981	117	376	4,700	62	22
1980	90	234	4,230	46	22

A-6: Unit Cost of Construction of Hydraulic Structures

Pipe unit prices for desired pipe diameter. Source: TWDB Unified Costing Model User's Guide - 2013				
Diameter	**Rural Cost with Appurtenances Soil**	**Rural Cost with Appurtenances Rock**	**Urban Cost with Appurtenances Soil**	**Urban Cost with Appurtenances Rock**
(inches)	**($/Foot)**	**($/Foot)**	**($/Foot)**	**($/Foot)**
6	$18	$22	$25	$30
8	$28	$34	$39	$47
10	$31	$38	$44	$53
12	$35	$41	$48	$58
14	$46	$55	$64	$77
16	$57	$68	$80	$96
18	$68	$82	$96	$115
20	$80	$95	$111	$134
24	$102	$122	$143	$171
30	$136	$163	$190	$228
36	$169	$203	$237	$285
42	$203	$244	$284	$341
48	$237	$284	$332	$398
54	$271	$325	$379	$454
60	$304	$365	$426	$511
66	$356	$427	$498	$598
72	$416	$500	$583	$700
78	$487	$585	$682	$819
84	$570	$684	$798	$958
90	$667	$800	$934	$1,121
96	$767	$921	$1,074	$1,289
102	$859	$1,031	$1,203	$1,443
108	$945	$1,134	$1,323	$1,588
114	$1,040	$1,247	$1,455	$1,746
120	$1,144	$1,372	$1,601	$1,921
132	$1,315	$1,578	$1,841	$2,209
144	$1,512	$1,815	$2,117	$2,541

Unit Cost for Pumps. Source: TWDB Unified Costing Model User's Guide - 2013		
Horsepower	**Booster Pump Cost**	**Intake Station Cost**
5	$602,000	
10	$662,000	
20	$695,000	
25	$730,000	
50	$766,000	
100	$804,000	
200	$1,616,000	$2,000,000
300	$1,778,000	$2,500,000
400	$2,254,000	$3,000,000
500	$2,318,000	$3,500,000
600	$2,381,000	$4,000,000
700	$2,445,000	$4,500,000
800	$2,880,000	$5,000,000
900	$2,990,000	$5,500,000
1000	$3,100,000	$6,000,000
2000	$4,201,000	$8,400,000
3000	$5,301,000	$9,700,000
4000	$6,401,000	$11,000,000
5000	$7,501,000	$12,000,000
6000	$8,602,000	$13,000,000
7000	$9,702,000	$14,000,000
8000	$10,802,000	$15,000,000
9000	$11,902,000	$16,000,000
10000	$13,003,000	$17,000,000
20000	$24,005,000	$28,000,000
30000	$28,806,000	$37,000,000
40000	$36,008,000	$47,000,000
50000	$45,009,000	$56,000,000
60000	$54,011,000	$65,000,000

A-7: Historic Municipal and Industrial Water Consumption in Matagorda County

Table was adapted based on the data of TWDB Historical Water Use

Year	Population	Municipal (ac-ft)	Industrial (ac-ft)
2000	37,957	5,420	10,416
2001	38,173	4,904	6,864
2002	37,945	4,599	7,486
2003	38,007	5,011	11,862
2004	37,767	4,812	10,888
2005	37,331	4,690	7,590
2006	37,063	4,515	9,011
2007	36,923	4,354	8,155
2008	37,375	4,600	8,209
2009	37,439	5,047	3,967
2010	36,702	4,956	3,572
2011	36,836	6,019	4,248
2012	37,132	5,202	4,613
2014	36,694	4,486	4,605