ENERGY PORTFOLIO ASSESSMENT TOOL (EPAT): SUSTAINABLE ENERGY PLANNING USING THE WEF NEXUS APPROACH – TEXAS CASE STUDY

A Thesis

by

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MASTER OF SCIENCE

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ABSTRACT

The future energy portfolio at the national and subnational levels should consider its impact on water resources and environment. Although energy resources are the main contributors to the national economic growth, these resources must not exploit other primary natural resources. A study of the connections between energy and natural systems, such as water, environment and land, is required prior to proceeding to energy development. Policy makers are in need of a tool quantifying the interlinkages across energy, water and the environment, while demonstrating the consequent trade-offs across the nexus systems. The Energy Portfolio Assessment Tool (EPAT) is a tool enabling the user to create different energy portfolio scenarios with various energy and electricity sources, and evaluate the scenario's sustainability environmentally and economically. The Water-Energy-Food nexus systematic approach is the foundation of the EPAT framework. Texas is a suitable geographical region to study and assess the current and future implications of energy portfolios. The research evaluates the impact of the current and projected Texas energy portfolios on water and the environment, taking into consideration production, generation and production change. The three scenarios are: Reference Case - 2015, CPP with Energy Reference Case - 2030, and No CPP with Energy Reference Case - 2030. In the presence of the CPP, total water withdrawal is expected to decrease significantly, while total water consumption is projected to experience a shy decrease due to the increase in water consumption in electricity generation caused by the new electricity mix. The CPP is successful in decreasing emissions, but is accompanied by tradeoffs, such as increasing water consumption and land use by electricity generation. The absence of the CPP will lead to an extreme surge in total water withdrawn, consumed and emissions. Therefore, conservation policies should move from the silo to the nexus mentality to avoid unintended consequences as improving one part of the nexus could end up worsening the other parts.

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NOMENCLATURE

BTU	British Thermal Unit
CC	Combined Cycle
CEG	Total carbon footprint of electricity generation portfolio (g CO_2)
CEP	Total carbon footprint of energy production portfolio (g CO_2)
CECO	Cost of coal electricity generation ($/GJ)
CEHY	Cost of hydro electricity generation ($/GJ)
CENG	Cost of natural gas electricity generation ($/GJ)
CENU	Cost of nuclear electricity generation ($/GJ)
CESO	Cost of solar electricity generation ($/GJ)
CEWI	Cost of wind electricity generation ($/GJ)
CGCO	Carbon footprint factor for coal electricity generation (g CO_2/GJ)
CGHY	Carbon footprint factor for hydro electricity generation (g CO_2/GJ)
CGNG	Carbon footprint factor for natural gas electricity generation (g CO_2/GJ)
CGNU	Carbon footprint factor for nuclear electricity generation (g CO_2/GJ)
CGSO	Carbon footprint factor for solar electricity generation (g CO_2/GJ)
CGWI	Carbon footprint factor for wind electricity generation (g CO_2/GJ)
CO_2	Carbon Dioxide
CPOL	Carbon footprint factor for oil energy production (g CO_2/GJ)

CPBE	Carbon footprint factor for bioenergy production (g CO_2/GJ)
CPCO	Carbon footprint factor for coal energy production (g CO_2/GJ)
CPNG	Carbon footprint factor for natural gas energy production (g CO_2/GJ)
$CTCO_{ij}$	Fraction of coal electricity generated by generator i & cooling type j (%)
$CTNG_{ij}$	Fraction of natural gas electricity generated by generator i using cooling type j (%)
$CTNU_i$	Fraction of nuclear electricity generated by generator i & cooling type j (%)
EGC	Total cost of electricity generation portfolio ($)
EGCO	Annual electricity generation from coal (GJ)
EGHY	Annual electricity generation from hydro (GJ)
EGNG	Annual electricity generation from natural gas (GJ)
EGNU	Annual electricity generation from nuclear (GJ)
EGSO	Annual electricity generation from solar (GJ)
EGWI	Annual electricity generation from wind (GJ)
EPBE	Annual energy production from bioenergy (GJ)
EPCO	Annual energy production from coal (GJ)
EPNG	Annual energy production from natural gas (GJ)
EPOL	Annual energy production from oil (GJ)
Gal	Gallons

GJ	Giga Joules
GT	Gas Turbine
$GTCO_i$	Fraction of coal electricity generated by type of generator i (%)
$GTNG_i$	Fraction of natural gas electricity generated by type of generator i (%)
GTNU	Type of nuclear electricity generator
$GTSO_i$	Fraction of solar electricity generated by type of generator i (%)
IGCC	Integrated Gasification Combined Cycle
kWh	Kilo-Watt-Hour
km^2	Kilometers squared
Mgal	Million Gallons
MWh	Mega-Watt-Hour
USD	United States Dollars
$PTOL_i$	Fraction of oil energy produced by type of production i (%)
RUOL	Fraction of water reused in oil production (%)
$PTNG_i$	Fraction of energy natural gas produced by type of production i (%)
RUNG	Fraction of water reused in natural gas production (%)
PTCO	Coal energy by type of production (%)
$PTBE_i$	Fraction of bioenergy produced by type of production i (%)
LEP	Total land footprint of energy production portfolio (m^2)
LPOL	Land footprint factor for oil production (m^2/GJ)
LPNG	Land footprint factor for natural gas production (m^2/GJ)

LPCO	Land footprint factor for coal production (m^2/GJ)
LPBE	Land footprint factor for bioenergy production (m^2/GJ)
LEG	Total land footprint of electricity generation portfolio (m^2)
LGNG	Land footprint factor for natural gas electricity generation (m^2/GJ)
LGCO	Land footprint factor for coal electricity generation (m^2/GJ)
LGNU	Land footprint factor for nuclear electricity generation (m^2/GJ)
LGWI	Land footprint factor for wind electricity generation (m^2/GJ)
LGHY	Land footprint factor for hydro electricity generation (m^2/GJ)
LHSO	Land footprint factor for solar electricity generation (m^2/GJ)
MTon	Million Tons
REP	Total revenue of energy production portfolio ($)
SPOL	Spot price of one barrel of oil ($/GJ)
SPNG	Spot price of one MMBtu of natural gas ($/GJ)
SPCO	Spot price of one short ton of coal ($/GJ)
SPBE	Spot price of one gallon of ethanol ($/GJ)
ST	Steam Turbine
$WCCO_{ij}$	Water consumption factor for coal generator i & cooling type j (gal/GJ)
WCHY	Water consumption factor for hydro electricity generation (gal/GJ)
$WCNG_{ij}$	Water consumption factor for natural gas generator i using cooling type j (gal/GJ)

$WCNU_i$	Water consumption factor for nuclear generator i & cooling type j (gal/GJ)
$WCSO_i$	Water consumption factor for solar electricity generator i (gal/GJ)
WCWI	Water consumption factor for wind electricity generation (gal/GJ)
WEF	Water-Energy-Food
WCGCO	Total water consumed for coal electricity generation (gal)
WEGHY	Total water consumed for hydro electricity generation (gal)
WCGNG	Total water consumed for natural gas electricity generation (gal)
WCGNU	Total water consumed for nuclear electricity generation (gal)
WEGSO	Total water consumed for solar electricity generation (gal)
WEGWI	Total water consumed for wind electricity generation (gal)
WEPBE	Water consumed for bioenergy production (gal)
WEPCO	Water consumed for coal energy production (gal)
WEPNG	Water consumed for natural gas energy production (gal)
WEPOL	Water consumed for oil energy production (gal)
$WPBE_i$	Water consumption factor for type of production i for bioenergy (gal/GJ)
WPCO	Water consumption factor for type of production for coal (gal/GJ)
$WPNG_i$	Water consumption factor for type of production i for natural gas (gal/GJ)
$WPOL_i$	Water consumption factor for type of production i for oil (gal/GJ)
WRCO	Water consumption factor for refining coal (gal/GJ)

WRNG	Water consumption factor for refining natural gas (gal/GJ)
WROL	Water consumption factor for refining oil (gal/GJ)
$WWCO_{ij}$	Water withdrawal factor for coal generator i & cooling type j (gal/GJ)
$WWNG_{ij}$	Water withdrawal factor for natural gas generator i using cooling type j (gal/GJ)
$WWNU_{i}$	Water withdrawal factor for nuclear generator i & cooling type j (gal/GJ)
WWGCO	Total water withdrawn for coal electricity generation (gal)
WWGNG	Total water withdrawn for natural gas electricity generation (gal)
WWGNU	Total water withdrawn for nuclear electricity generation (gal)

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

1.1. Introduction

"When the well is dry, we learn the worth of water."

\- Benjamin Franklin

People living in modern societies, such as the United States of America, expect the immediate supply of water and energy through an opening of a faucet, and a flip of a switch. However, the American consumer is unaware of the significant connection between water and energy, and vice versa. This lack of awareness of the deep connection between water and energy has led to a water resource abuse on both the subnational and national level.

Water, food and energy are not only greatly interlinked, but are almost dependent on one another to function. From the energy point of view, water and food require energy as an input. For example, energy is needed to extract, desalinate, treat and transport water to end users. In addition, energy is also required to process and produce food. Therefore, energy security is crucial in order maintain water and food supply. At the same time, from a water point of view, energy and food require water as an input to perform. Huge amounts of water are needed for energy production and electricity generation, such as extracting and refining fossil fuels, and cooling power plants. Nonetheless, water is also essential for food production. Similarly, water security is also crucial in order to secure future energy and food supply. The water-energy-food nexus ensures efficient and productive use of natural resources. In other words, the water-energy-food nexus works in increasing the sustainability of all the systems. The interlinkages, effecting parameters and flows between the three systems are shown in Figure 1 below.

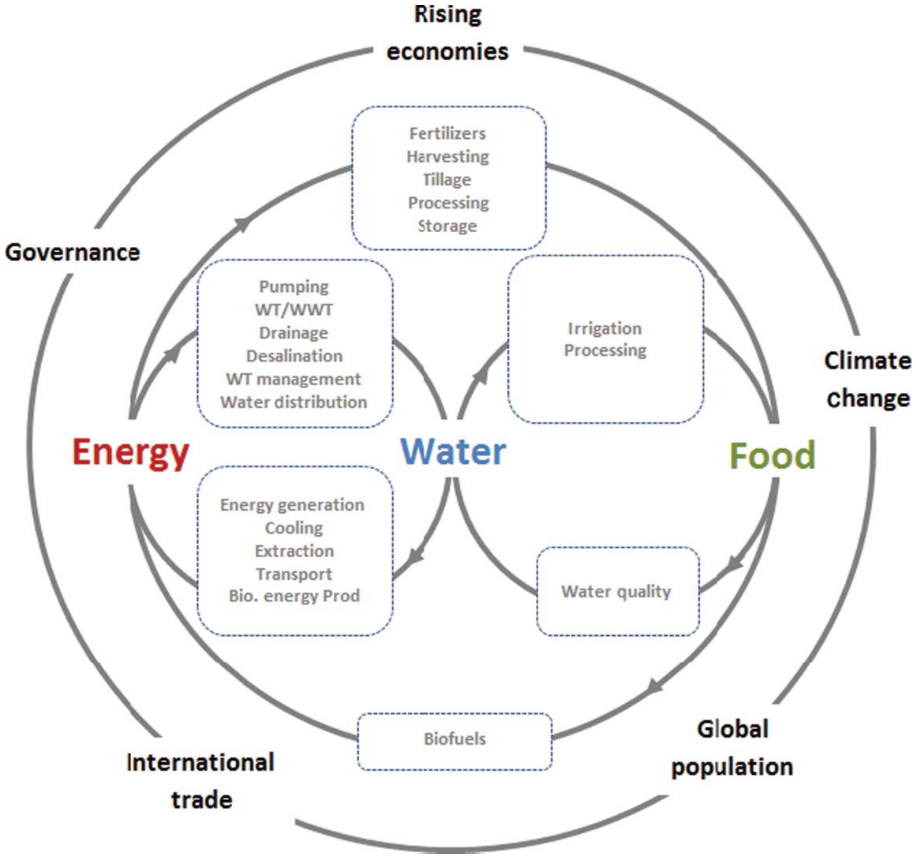


Figure 1 The WEF nexus with water, energy and food flows, and effecting parameters (Mohtar, 2012)

Energy demand is rising, and consequently the water demand by the energy sector is also rising. Nowadays, all phases of energy production and electricity generation use water. Up to this date, water and energy are each regulated independently, and the nexus is starting to gain attention both on a national and international level (Hussey & Pittock, 2012).

The water-energy nexus has only recently become an interest for research and public (Webber, 2008). Past experiences have taught us that working in silos is not the way to go when creating water and energy policies. Policy makers often disregard the interconnectedness of water and energy, and as a result, come out with contradicted water and energy policies (Poumadere et al, 2005). Water policy makers try to find the optimal solution that ensures sustainability of its resources, and at the same time, energy policy makers do the same, but from an optimization point of view, neither is an optimal solution because the systems were decoupled. Working in silos exposes the water and energy systems, and introduces vulnerabilities. Vulnerabilities include droughts, heat waves, contamination, grid outages, and unfair competition for water.

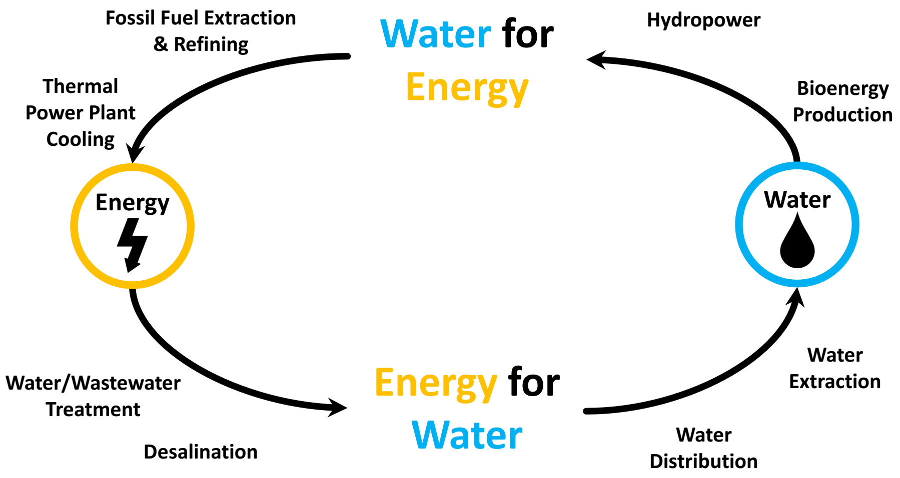


Figure 2 Schematic showing the water–energy nexus with interconnected parameters

Along with energy consumption and production comes water consumption. Water is needed both in energy production, such as in oil and gas production, and in power generation, such as in thermal power plants, and the whole water-energy nexus is shown in Figure 2 above.

The drilling process for both conventional and unconventional sources of natural gas is a major water consumer. Unconventional sources of natural gas, such as shale gas, are rapidly increasing, specifically in Texas. These unconventional sources require new unconventional drilling techniques (Rahm, 2011). Hydraulic fracking is an unconventional drilling technique that includes horizontal drilling and multistage fracturing using water jets to get the shale gas reserves. The use of the hydraulic fracturing technique has resulted in some environmental concerns, especially on the water fortune. The natural gas produced from shale plays is through hydraulic fracturing. The technique uses extensive amounts of water throughout its process, in drilling and fracturing. This substantial amount of water used in the technique is the main reason behind the environmental concern. Moreover, along with the enormous water withdrawal, hydraulic fracturing is associated with water reservoir contamination, and great land usage. According to the Environmental Protection Agency (EPA), the hydraulic fracturing technique uses 2 to 5 million gallons of water per well (EPA, 2010b). During the hydraulic fracturing operation, some fluids rise to the surface. This wastewater fluid is mainly comprised of the fluid used to drill and fracture the shale plays; water and chemical additives. Several methods of wastewater disposal are currently being used, such as underground deep injection and discharge to surface water after treatment (Office of Research and Development, 2010). Issues concerning hydraulic fracturing lie squarely at the center of the water, energy food nexus. The push for hydraulic fracturing is framed as a matter of energy security, yet both come with potentially significant costs to the security of our water resources (Hanlon et al., 2013).

On the other hand, electric power production is a huge water dependent sector, as cooling systems in power plants withdraw and consume large amounts of water. Water is crucial for electricity generation, and electricity generating power plants are the primary victims of a drought. Cutting off water supply for cooling, leads to reduction in operations and maybe even black outs (Hanlon et al., 2013). The majority of the region's current and projected electricity generation are coming from fossil fuel and nuclear power plants. These power plants are in need of a constant supply of cooling water to maintain the plant's operational temperature. In the near future, some utility expansion plans could require large additional water for cooling that it might cause water shortages during high temperature times in some parts of the country (Sovacool & Sovacool, 2009). Water consumed in electric power generation cannot be further utilized for other purposes, such as urban, agricultural or environmental. Cooling systems are impacting local rivers and aquifers by tying up huge amounts of water that could be used for other purposes. In the process of utility planning and power plant development, the cost of using water for electricity generation is not considered over the life span of the power plant. The power plant impact of on water greatly differs depending on the adopted technology. For example, a wet-cooled coal power plant uses three times more water than a combined-cycle gas power plant (Wester Resource Advocates, 2011).

The U.S. energy system is at risk of becoming vulnerable amidst the water resource scarcity and uncertainty. As a matter of fact, the severe drought that hit the United States back in 2012, along with Hurricane Sandy and the recent boom in the oil and gas sector caused by hydraulic fracturing have initiated a national dialogue addressing the relationship between water and energy and the future. The dialogue is set to discuss the impact of several factors on the water-energy nexus. Two of these factors are future energy portfolios and climate change. The United States have already begun sensing the impact of future energy portfolios and climate change through increased temperature and minimized precipitation patterns. Population growth in the United States is also a factor as it reflects an increase in water and energy supply, posing a necessity in proper water and energy management in the planning of future energy portfolios. The dialogue also addressed emerging technologies capable of optimizing water use in energy production and electricity generation (DOE, 2014). In brief, the future of the water for energy nexus depends on several factors: future energy portfolios, technology options, and energy activities. The water for energy nexus will try to coordinate and manage the water use in energy systems and sustain resources for future generations.

Texas represents a convenient geographical region to study and assess the current and future implications of energy portfolios, and the connection between water and energy. The size of Texas is suitable for pilot analysis, yet due to its large area, the results can be reflected to a national level. Texas is a major water consumer, due to its large population, and most importantly its huge energy sector. According to the U.S. Energy Information Administration (EIA), the great state of Texas currently sits on the throne of energy production in the United States, leading the nation in crude oil and natural gas production. Texas is a major player in natural gas resources having an estimated 6,676 million barrels of natural gas contained in proved reserves, around 44% share of U.S. total (EIA AEO, 2016). Unconventional gas, or shale gas, is extracted using hydraulic fracking.

Three significant shale gas plays are located in the state of Texas: Barnett Shale, Eagle Ford Shale and Permian Basin. Furthermore, Texas is the largest generator and consumer of electricity in the United States, it produces and consumes around 400 billion kWh of electricity annually. Moreover, it currently is the number one producer of wind power in the United States, and sixth worldwide (compared to countries) (EIA 2016). The state's climate is generally warm all over, moist at the Gulf of Mexico and less moist deeper into the state. As temperature and humidity levels fluctuate around the comfort levels, residential, commercial and almost all envelopes turn on air conditioning and space-heating to reach the comfort zone. Moreover, in some states, such as Texas, seasonal variations usually correlate with electricity demand trends (Ackerman & Fisher, 2013). Texas has the second largest population and second largest economy in the nation, after California, making it a huge energy demander. The industrial sector in the state of Texas, mainly oil and gas production, has the largest share of the energy consumption. Due to state's climatic, populistic and economic conditions, Texas is the number one energy consumer nationwide, almost 12.5% of the United States' total.

In 2011, the Texas Water Development Board (TWDB) declared: *"In serious drought conditions, Texas does not and will not have enough water to meet the needs of its people, and its businesses, and its agricultural enterprises."* In other words, Texas is coming to an approximate 40% water gap in the year of 2070 (TWDB - SWP17). The projected water demand and supply in the state of Texas is shown below in Figure 3. We already have a small water gap, and this water gap is set to increase further should the current poor water management continue. No doubt, future energy policies will play a huge role in mitigating the future shortage, but till now, the problem remains unaddressed (Hanlon et al., 2013).

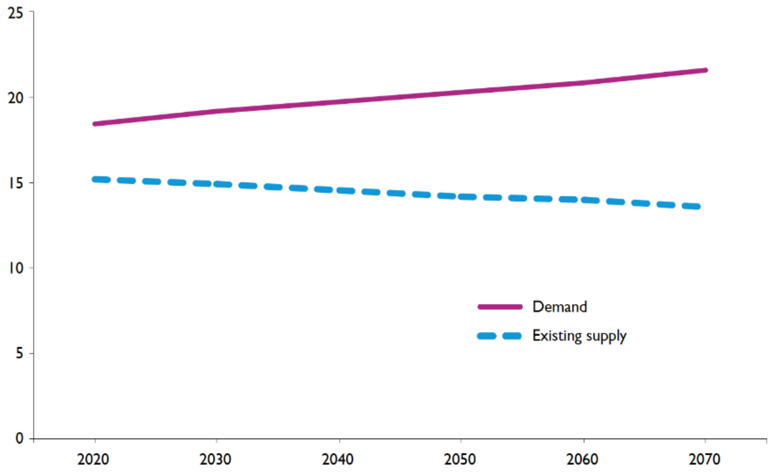


Figure 3 Projected annual water demand and existing water supply in Texas (million acre-feet of water) (TWB - SWP17, 2017)

Vulnerabilities will possibly become more evident as resources become more constrained, and water-energy suppliers encounter new challenges, such as water quantity and quality associated with climate change (Intergovernmental Panel on Climate Change, 2008).

Understanding the water-energy nexus is essential to sustainable development and natural resource policies. To obtain a sustainable and robust system forward, we have to use a systematic approach for policy making, such as the Water-Energy-Food Nexus methodology.

1.2. Research Objectives

- To develop a tool to assess energy portfolios, and quantify interlinkages between energy, water, emission, land and energy economics.

- To assess the sustainability of current and EIA projected energy portfolios in Texas using the energy portfolio assessment tool, taking into consideration water conservation, environmental impact and energy economics.

1.3. Literature Review

1.3.1. Gap Identification and Tool Review

Energy security for current and future generations is a top priority for all nations, for energy is the fuel and the engine driving the economy. At the same time, securing water supplies, clean environment and sustainable economies are also of equal significance. Therefore, achieving energy security in a sustainable manner is a complex challenge. Policy makers governing energy, water and other resources have a major task at hand, as they are the major stakeholders in the journey to a sustainable future (Daher, 2015). So far, the focus of energy policy makers has been on securing the supply of energy and electricity for growing populations and economies. This approach has worked reasonably well, but not really well. Focusing only on energy without looking at the tradeoffs works well when natural resources are abundant, such as energy and water, no climatic challenges, externalities were considered secondary and when the energy options are limited. The world has changed now, as climate changed has become a serious global concern, clean renewable energy advanced in an unprecedented rate, water-energy efficient technologies have improved vastly, and competition on natural resources, such as land and water, has become fiercer than ever. Hence, policy makers are in need of a holistic framework that connects systems while displaying the resulting tradeoffs to better help understand the effects systems have on one another (Mohtar, 2012). Some policy makers may be aware of the nexus approach, but continue to work in silos within the nexus. This leads to unintended consequences as improving one part of the nexus could end up worsening the other parts.

Policy makers are in need of a tool quantifying the interlinkages across energy, water and the environment. The policy maker is lacking efficient tools to evaluate the sustainability of energy portfolios while demonstrating the consequent trade-offs across the nexus systems. Scenario-based assessment tools enable policy makers to better plan future energy portfolio scenarios. Tools that address the general and specific aspect of the energy impact in the nexus already exist. These tools include LEAP (SEI, 2013), CLEWS (KTH, 2013), Global Calculator (IEA, 2014), and many others. LEAP (Long-range Energy Alternatives Planning System) is a tool that analyses energy policy effects on the climate, and assesses mitigation approached to climate change. CLEWS (Climate, Land, Energy and Water Strategies) is a tool that addresses the issues of the interconnected resources in a systems approach to determine their interactions. Global Calculator is a tool that views consequences of pathways in energy, food and land on the climate by linking energy to lifestyle. A list of nexus tools is also found in IRENA (2015).

All these tools address the energy part of the nexus, and each tool has a unique approach in analyzing the energy resources and their interactions with climate and land. A brief description of these tools is found in table 5.

However, even with all existing tools policy makers are still missing energy assessment tools that are:

- Comprehensive
- Multi-scale
- Quantify interconnectivity between energy, water, land, climate and economics
- Helps sustainable energy growth for future generations
- Supports holistic integrative energy resources management

Table 1 Review of nexus tools (IRENA, 2015; Strapasson et al, 2014)

	INPUTS		**OUTPUTS**	
Tools	**Main Inputs**	**Energy**	**Water**	**Food**
LEAP	Extensive data requirement. Techno-economic details of energy technologies.	Detailed analysis of energy demand, transformations and stocks. Energy balances.	Watershed hydrology and water planning Physical and geographical simulation water demands and supplies. Groundwater, water quality and conservation, reservoirs and hydropower.	
CLEW	Extensive data requirements. Technical and economic parameters of power plants, farming machinery, water supply chain, desalination terminals, irrigation technologies, fertilizer production, etc.	Energy balance, including power generation and refining. Energy for Food. Foreign (virtual) energy.	Water balance. Water supply and desalination. Water pumping. Water for food. Water for energy (hydropower, power plant cooling, biofuel crops).	Irrigation technologies. Use of fertilizers. Use of farming machinery.
Global Calculator	Global scale. Minimum data available. Very general.	Fixed pre-created global energy scenarios. Very general and basic technology and fuel alteration.		Land use. Farm yields and practices. Very basic and general diet alteration.

Thus, the need remains for a generic, holistic framework that considers the existing interlinkages between the systems and offers decision/policy-makers a solid foundation for debate, discussion and action.

CHAPTER II

STATUS OF THE WATER-ENERGY NEXUS IN TEXAS

2.1. Water for Energy in Texas

Water for energy in Texas consists of two major users: oil and gas industry and Power Utilities. Texas Water Development Board uses different titles: mining and steam-electric. Mining includes all processes of oil, gas and coal production, such as exploration, development and extraction. Steam-electric water demand is simply water for electricity generation. It mainly consists of diverting water from available sources for cooling. As you can see in the figures below, mining and steam-electric water demands represented only 4% of the total water used in the state in 2012, totaling to 682,000 acre-feet. Compared to other sectors the number is surely almost negligible, but mining and steam-electric water demands cause local problems, especially in areas prone to droughts.

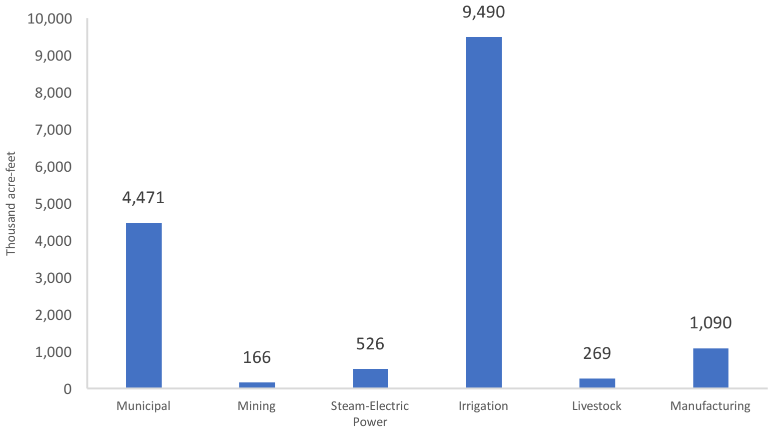


Figure 4 Statewide water use in 2012 (TWDB, 2015)

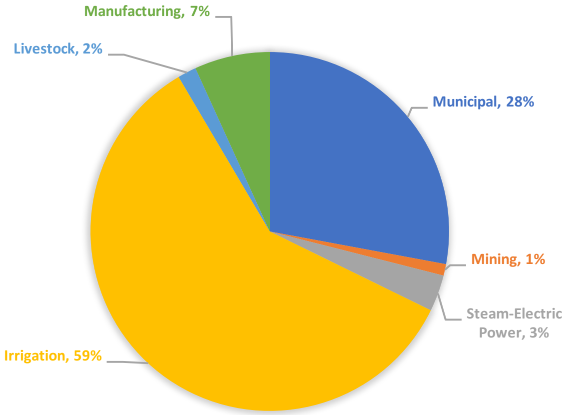


Figure 5 Statewide water use in 2012 by percentage (TWDB, 2015)

According to the “2017 State Water Plan” report by TWDB, water demand for mining is projected to decrease continuously in the future, yet maintaining a 1 to 2 percent share of the total state demand. To be more specific, hydraulic fracturing alone will consist almost 1% of the total state’s demand from 2020 to 2070. Unlike mining, water demand for steam-electric is expected to rise year after year, as shown in figure 6 below. The majority of future water demand for steam-electric is projected remain in the same counties in which current plants exist (TWDB, 2017).

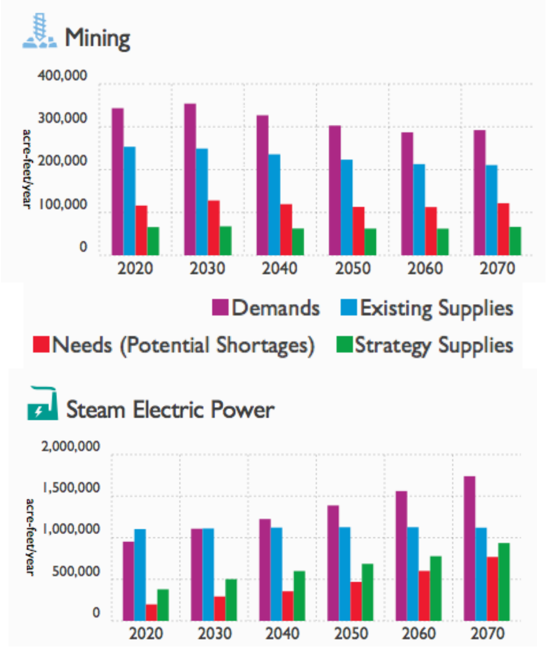


Figure 6 Projected water use for mining and steam-electric (TWDB, 2017)

In this section, we discuss water portfolios for energy production and electricity generation in Texas. It is essential to draw lines from water sources to water sinks. By doing that, we can visualize the effect of energy on water sources by type, such as ground, surface, fresh, saline water and many others. Doing that allows us the full confidence to perform interventions, or outline conservation pathways when planning and implementing energy portfolios.

2.1.1. Water for Energy Production

Texas leads the nation in crude oil and natural gas production. In 2014, Texas produced over one million thousand barrels of crude oil, and the last time oil production volume surpassed a million thousand barrels was back in 1979. Similarly, and during the same year, Texas produced almost 8 millions of million cubic feet of natural gas, clearly showing the impact of hydraulic fracturing, as since the boom back in 2011, the production has increased by almost 300,000 million cubic feet a year. Nonetheless, Texas is also a producer of coal (largest lignite producer in the U.S.), nuclear energy and renewables (Texas Energy Profile EIA, 2016). In terms of BTU of energy produced, figure 7 and table 1 show the percentage and amount of energy produced per source in the year of 2014.

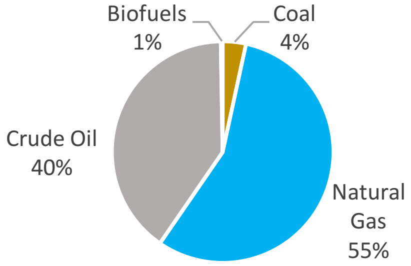


Figure 7 Percentage energy production by source in Texas (Texas Energy Profile EIA, 2016)

Table 2 Energy production by source in Texas 2014 (Texas Energy Profile EIA, 2016)

Fuel Type	Production (Trillion BTU)
Coal	568
Natural Gas	9,380
Crude Oil	6,703
Biofuels	44

Substantial amounts of water are required for the production of oil, natural gas and coal. The process of transforming the raw fossil fuel material into usable forms of liquid fuels it also water intensive. In energy, water consumed and water withdrawn do not mean the same thing. Water withdrawn represents the total amount of water extracted. Water consumed is the withdrawn water used and not returned to the source. In energy operations, the amount of water withdrawn is much greater than the amount of water consumed. Nonetheless, the intensity of withdrawn water is also important because for water to be withdrawn, a water body or water source must be available (World Economic Forum, 2011).

From 2008 to 2011, the water used for hydraulic fracturing increased by 126% according to Bureau of Economic Geology, from 36,000 AF to 81,500 AF. On the other hand, the percentage of water recycling and reuse increased to 21%, meaning 17,000 AF of the total water used for hydraulic fracturing in 2011 came from recycled and reused water. The published report by the Bureau of Economic Geology, titled "Oil & Gas Water Use in Texas: Update to the 2011 Mining Water Use Report", strongly points out that the oil and gas industry has been decreasing its freshwater use even with its increase in water demand (BEG, 2012). Brackish water also, along with recycled and reused water, is being used in oil and gas activities.

Oil and gas industry water use in activities such as drilling, hydraulic fracturing and water flooding is expected to keep on increasing peaking at 340,000 AF/yr in 2030. The oil industry alone accounts for a maximum of 180,000 AF/yr in 2030. The annual water use in hydraulic fracturing is projected to peak in the late 2020's reaching 125,000 AF. However, as stated earlier, this increase in water demand does not translate into an increase in freshwater use, as freshwater use is projected to remain almost stable at 70,000 AF/year through the next 40 years (BEG, 2012). New water, such as brackish, recycled, reused and maybe desalinated are expected to feed into the water demand by the oil and gas industry. In 2015, mining activities accounted for 1% of the total water used in the state (TWDB, 2015). This number might seem negligible, but what is often neglected by policy makes and industry that this 1% is unevenly distributed across the state land, and poses threats to local water resources.

Total water use is uneven across the various plays and locations. More importantly, groundwater and surface water usage is also not equal, as it depends on local conditions even within the single play. In some areas, groundwater (fresh and brackish) use is the dominant source, such as in East Texas, and in other areas surface water is the dominant, such as in West Texas. Reused water is always fed into water streams in oil and gas activities, but it is limited by the amount of flow back as it varies from one play to another (BEG, 2012).

Plays are spread all around in Texas, and each play has a unique portfolio or combination of water sources feeding into the oil and gas activities depending on the available water resources. There are 3 major shale plays for hydraulic fracturing in Texas: Barnett Shale, Eagle Ford, and Permian Basin. These three plays are responsible for 80% of the total water used for hydraulic fracturing. The Barnett Shale and the Eagle Ford shale together consisted for more than 50% of the total water used for hydraulic fracturing, around 25,000 AF each. The Permian Basin on the other hand used around 15,000 AF (BEG, 2012), as shown below in figure 8.

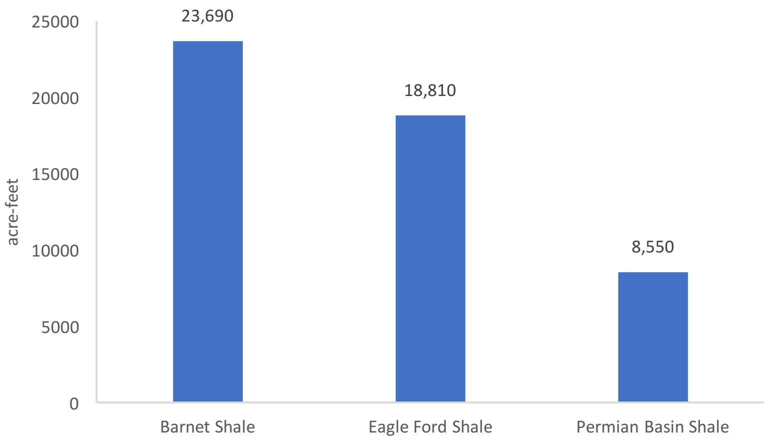


Figure 8 Water use for hydraulic fracturing in the three major plays in Texas (BEG, 2012)

The percentage of water sources and types consumed in the major shale plays of Texas are shown in table 2. The Barnett Shale is the play with the longest history, and its water portfolio is 80% surface water, and 20% ground water. The vast majority of the surface water (92%) is fresh water, whereas the ground water is split into fresh, brackish and reused. Projections in the Barnett Shale suggest a small water use increase in the next 20 years, but not an increase in water consumption, as operators looking to expand water portfolio resources and decrease dependency on freshwater (BEG, 2012).

In the Eagle Ford Shale, operators rely only groundwater resources (90%). Freshwater comprises 80% of the total ground water used, the other 20% is mainly brackish water. The Eagle Ford Shale is unique, because unlike other plays, projections indicate a slight decrease in water use in the foreseeable future. This slight decrease is because in some areas within the play, the industry switched from slick-water fracturing to gel fracturing that uses less water. The Eagle Ford is the only play where in the coming years is expected to hold a steady value in water usage (BEG, 2012).

In the Permian Basin, nearly all water used is from underground resources. A significant amount of brackish water is being used (30%). Operators in the Permian Basin do not do much in water reuse and recycling, but some companies use produced water from conventional oil and gas operations. Projections show that brackish water percentage will increase in the coming years, and water consumption will decrease amidst water use increase. On the other hand, fresh water usage is to remain stable (BEG, 2012).

Table 3 Percentage of fresh, brackish, reused, ground and surface water used in major hydraulic fracturing plays in 2011 (BEG, 2012)

Play	Ground Water	Surface Water	Type	Percentage (%)
Barnet Shale	20%	80%	Fresh	95
			Brackish	3
			Reuse	5
Eagle Ford Shale	90%	10%	Fresh	80
			Brackish	20
			Reuse	0
Permian Basin	100%	0%	Fresh	20
			Brackish	80
			Reuse	0

2.1.2. Water for Electricity Generation

Thermoelectric power plants use water for power generation and cooling. Basically, there are two water loops within a thermoelectric power plant, internal and external. In the internal water loop, water is brought up to the steam phase by burning fossil fuels (coal, natural gas or oil) or nuclear fission, and then the energy accumulated in the steam rotates the blades of the turbine. The turbine is connected to a generator that translates rotary movement into electrical power. The process of power generation does not end here, the steam has to be condensed back into the liquid phase by using either water or air. Cooling, or steam contestation, is a vital process in power generation as the efficiency of the power plant depends on the level of cooling attained. However, the type of fuel, power generation technology, and cooling technology determine the amount of water required to generate electricity. Typically, cooling is performed by a heat exchange process between the internal and external water loops. Heat is transferred from the internal to the external loop via heat exchangers (Stillwell et al, 2011).

Renewables, natural gas, coal and nuclear constitute the power generation portfolio in Texas. Natural gas, coal and nuclear generate 90% of the electric power in Texas, while the remaining 10% are from renewable sources, mainly wind, as shown in figure 9 and table 3 below (Texas Energy Profile EIA, 2016). This 90% of electricity supply comes from water dependent power plants.

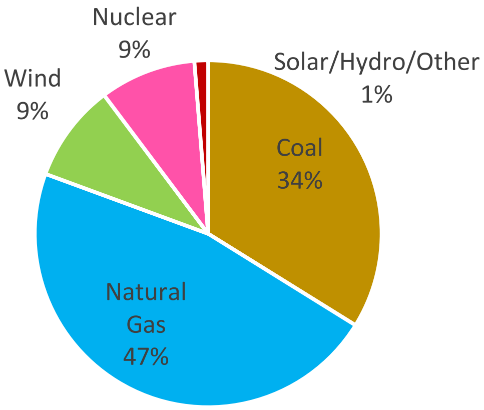


Figure 9 Percentage electricity generation by source in Texas (Texas Energy Profile EIA, 2016)

Table 4 Electricity generation by source in Texas (Texas Energy Profile EIA, 2016)

Fuel Type	Million MWh
Coal	148.17
Natural Gas	204.72
Wind	40.01
Nuclear	39.29
Solar/Hydro/Other	5.59

External water loops are of three types: open-loop cooling, cooling reservoir and cooling tower. The figures below are schematics of the different cooling technologies in thermoelectric power plants showing flows or energy, water and air. The open-loop cooling method first withdraws large volumes of water from a nearby water source, and second passes the withdrawn water through the heat exchanger once to cool down the steam. Consequently, the open-loop cooling consumed a small volume of water by evaporation, and hence this consumed water cannot be directly reused. The withdrawn water is passed through the heat exchanger, cooled down again, recycled, and then does the whole process again. More evaporation occurs in closed-loop cooling hence the water consumption volume is higher than that of open-loop cooling. Nevertheless, open-loop cooling technologies require enormous volumes of water, therefore almost all power plants with open loop cooling are sited near a large water body. An alternative to using water to cool down power plants, is dry cooling that uses air and fans. Air is blown via huge fans directly on the internal water loop to remove heat. Even though, dry cooling does not use water, removing heat with air is not efficient, and as a result causes the power generation efficiency to decrease. Also, air cooling requires a significant amount of energy to operate, therefore the overall efficiency of power plants operating on air cooling is significantly lower than those operating on water cooling (King et al. 2008).

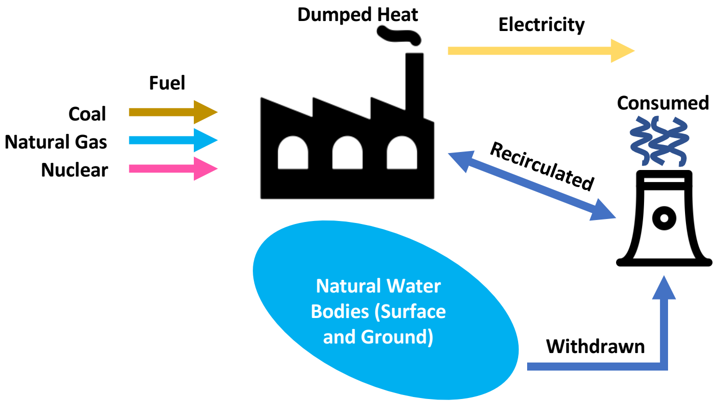


Figure 10 Schematic of a thermal power plant using a closed-loop cooling tower system, while showing energy and water flows.

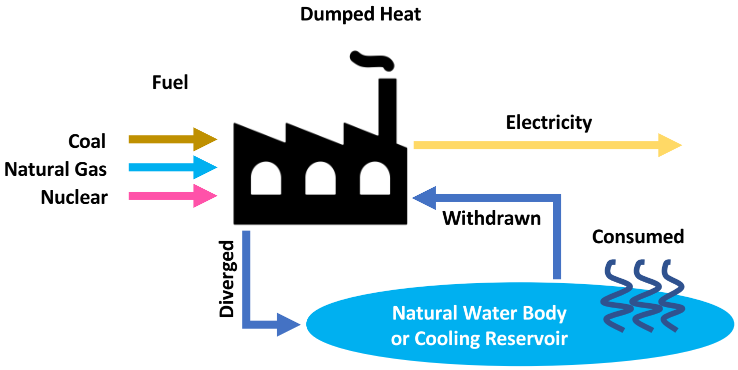


Figure 11 Basic schematic of a thermal power plant using an open-loop once-through cooling system, while showing energy and water flows.

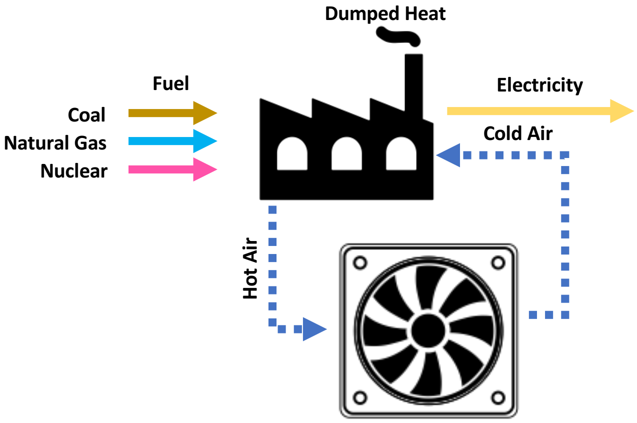


Figure 12 Basic schematic of a thermal power plant using an air cooling system, while showing energy and air flows.

A handful of power plants are using air-cooling, and are not exploiting any water sources (including natural gas combustion turbines in isolation or as part of combined cycle power plants) (Stillwell et al, 2011).

As we said earlier, water utilized in energy comes from different sources, and different properties. More than 90% of Texas, yet almost all power plants are cooled using surface water (King et al. 2008). The United States Geological Survey (USGS) categorized the water sources into 4 categories: surface water (SW), groundwater (GW), plant discharge (PD), and other (OT). Based on that data, in 2010, Texas withdrew 14,295 Mgal per day, and consumed 318 Mgal per day. Furthermore, 99% of withdrawn water came from surface water. Unlike energy production, where groundwater is the dominant water source, electricity generation almost solely relies on surface water sources. All in all, 3% of the total withdrawn water for cooling was consumed. Within the consumed numbers, 82% came from surface water, and the rest split equally between groundwater and plant discharge. An important remark is that 2% of the surface water withdrawn for cooling is consumed, whereas almost all what is withdrawn is consumed when it comes to groundwater (USGS, 2010). The data in table 4 illustrates the water withdrawal and consumption rates for cooling by source of water.

Table 5 Water withdrawn and consumed by water source for cooling in Texas 2010 (USGS, 2010)

EIA Water Source Code	2010 Withdrawal (Mgal/day)	2010 Consumption (Mgal/day)	Percent Consumption of Withdrawal	Percent of Total Withdrawal	Percent of Total Consumption
SW	14,212	259	2%	99%	82%
GW	42	26	82%	0.5%	9%
PD	31	27	87%	0.49%	8.5%
OT	1	1	70%	0.01%	0.5%
TOTAL	**14,295**	**318**	**3%**	**-**	**-**

However, the cooling technology determines the amount of water withdrawn and consumed. In Texas, almost all steam and combined cycle power plants use open-loop and closed-loop cooling, with these two constituting 85% of the cooling portfolio. The data collected from USGS for the state of Texas in 2010 show that generation is split almost equally between cooling technologies, with 51% from open-loop and 49% from closed-loop.

As revealed by the data, closed-loop cooling systems have higher values of water consumption, therefore consuming more than 80% percentage of water withdrawn. Water consumed by power plants comprised 2.5% of the total water consumed by all sectors in Texas (TWDB, 2007). Yet, this percentage only reflects the water consumed and not water withdrawn. The water withdrawal factor for cooling is always greater than that of consumption, especially for open-loop cooling where the withdrawal factor is extremely larger. In electricity generation, water withdrawal and consumption are essential for power generation planning and management. Specifically, power plants with open-loop cooling are constantly require a secure access to enormous volumes of water to be withdrawn for cooling. This kind of dependency introduces vulnerability into the system, as we cannot control or dodge droughts that result in water shortages, possibly leading to blackouts and shut downs. On the other hand, closed-loop cooling that use reservoirs restrain the water from being used for other purposes down along the stream (Stillwell et al, 2011). The biggest concern when it comes to water utilization in electricity generation is that the water available next to the power plants becomes constrained (Caputo, 2009).

CHAPTER III

METHODOLOGY

3.1. Water-Energy-Food Nexus Approach

Nations and states are constantly challenged to meet the increasing energy demands of its growing population and economy. Therefore, energy security is not only a top national priority, but also a matter of national security. Nevertheless, energy security should not be achieved amidst exploiting natural resources and the environment. Current mismanagement of natural resources will pose serious threats on the nation's water, energy and food security in the future. For example, an energy-centric policy has tradeoffs that impact water, land and the environment. Similarly, a water-centric policy has tradeoffs on energy, land and the environment. Therefore, the proposition of an appropriate policy that respect the links between the various natural systems is a basis to mitigating future security risks. Based on the energy portfolio scenarios of nations and states, this proposed framework is developed, identifying the environmental and economic resources that feed into creating them.

Energy-centric nations and states that rely on water-intensive technologies to meet their energy and water demands are faced by challenges of water dependency and availability. Water is neither evenly accessible throughout the year, nor evenly available across the state area. As a result, securing water supply is a constraint and a challenge for energy policy makers. Moreover, the uncertainty of water availability is a weak spot in the energy system, especially with the climate change factor. Think of water as a pie, with the energy, food, municipal, industrial and other sectors fighting over securing their share of the pie. The current inefficient, and unsustainable water allocation plan might be working now, but as population and economy grow, vulnerabilities will start to appear. This would be fine had we had infinite water resources. In order to support sustainable energy planning, a deep understanding of the impact of energy portfolios on water resources and the environment is required, as well as the sustainability cost accompanied with any proposed energy portfolio scenario. How should the energy production portfolio shift in order to reduce its water footprint and still meet the demands? How should electricity generation portfolio shift to become less water intensive without leading to reliability issues? What adjustment to the energy technology portfolio is required? What is the environmental and economic cost of the shift?

The Water-Energy-Food nexus systematic approach served as a foundation to the proposed framework. The WEF systematic approach considers the various interconnections between the studied systems, and eliminates the silos. The framework presented depicts “Energy” and “Water” as major dimensions, and “Land”, “Emissions” and “Economics” as minor dimensions. These dimensions are interlinked through parameters that reflect the effect of systems on each other. It is extremely important to evaluate the implications of a state’s energy portfolio on the natural resources and the environment. The methodology behind the proposed tool will be discussed through a conceptual and practical framework section. The conceptual and practical framework will provide the structure of the connections between the dimensions.

3.2. Energy Portfolio Assessment Tool (EPAT)

Having the interlinkages between water and energy in the state, we will then move to the second objective, we now move to targeting the first objective, which is the development of a tool to assess the sustainability of energy and electricity mixes. The tool developed in this research is called the Energy Portfolio Assessment Tool (EPAT).

3.2.1. Conceptual and Practical Framework

EPAT is a tool that enables the policy maker to create different energy portfolio scenarios with various energy and electricity sources, and evaluate the scenario's sustainability environmentally and economically. The tool is able to assess energy portfolios, taking as input energy production mix (GJ), electricity generation mix (GJ), and producing evaluated outputs such as water required (Mgal), economics of energy and electricity ($), carbon emissions (Ton CO_2), and land required (km^2). The tool will be used to work out the implications of the energy portfolio scenarios on the water, emission, land, cost and sustainability dimensions.

The EPAT framework is energy-centric. The tool allows the user to propose several energy portfolio scenarios for a nation, state or any geographic area. It grants the user the option to customize energy portfolios in terms of energy production and electricity generation. The user is able to create various energy portfolio scenarios composed of options of energy production sources, type of production, electricity generation sources, type of generator and type of cooling technology. By that, the impact of each energy production source and type, and each electricity generation source and type can be evaluated. Two data are required as input: energy production and electricity generation.

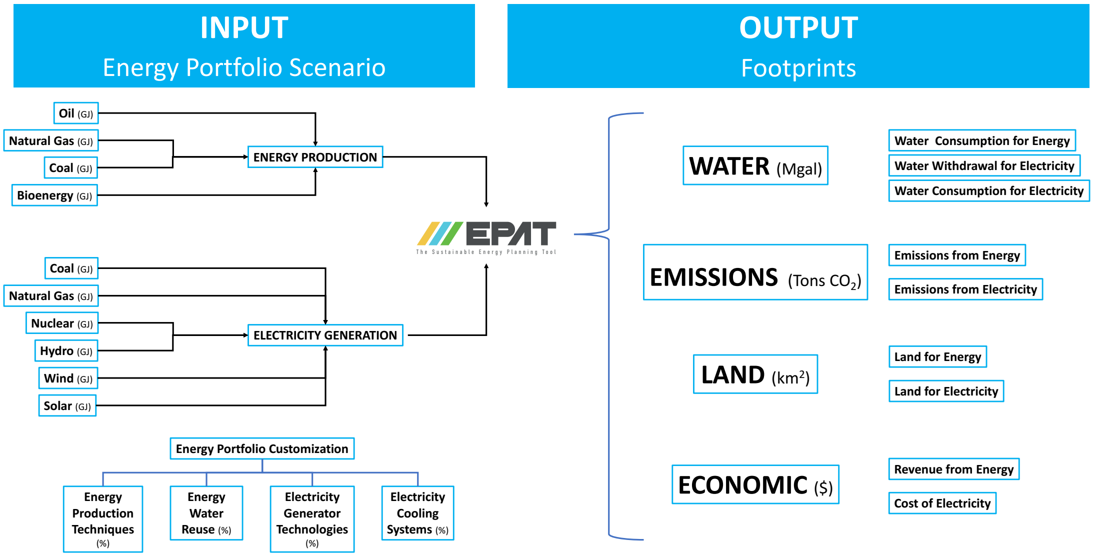


Figure 13 Input and output framework of EPAT

The inputs, energy production and electricity generation, are translated into evaluation outputs: water, land, emission, and energy economics. The water output quantifies the amount of water only consumed by the energy production, whereas both withdrawn and consumed by electricity generation. It displays the water footprint of each energy and electricity source. The land output calculates the impact of the energy portfolio on land, and how much land is engaged in energy production and electricity generation activities. The emissions output shows the associated carbon footprint of energy production and electricity generation. Last but not least, the economics output computes the revenue from energy production and cost of electricity generation of the electricity portfolio.

The input and output features will be explained extensively in the below sections, showing all calculations and assumptions adopted in the tool.

3.2.1.1. Energy Production Portfolio

For energy production, the tool was customized to include the energy sources, and techniques available in Texas. The tool requires the user to define the amount of energy produced by each source (GJ/year/source). The sources of energy production embedded in the tool are: oil, natural gas, coal, and bioenergy. The step that follows, which is the identification of the type of production for each source, is discussed in the "water for energy production" section.

3.2.1.2. Electricity Generation Portfolio

For energy electricity generation, similarly, the tool was customized to include the electricity sources, type of generators and cooling technologies in Texas. The user inserts the electricity generated by each source (GJ/year/source). The sources of electricity production in the tool are: natural gas, coal, nuclear, wind, hydro and solar. The further outlining of generation and cooling techniques are done in the "water for electricity generation" section.

3.2.1.3. Water for Energy Production and Electricity Generation

The energy sector is a major water user in an economy, through its energy production and refining, and electricity generation activities. Therefore, an extensive understanding of the energy-water link is required when addressing energy portfolio scenarios. The water withdrawal and consumption information are essential in order to evaluate the energy impact on water resources, and to check whether the area of study is capable of coping with the water demands of energy. Moreover, water withdrawal and consumption are not equal among energy production and electricity generation sources. A quantification of water usage is thus needed for every type of energy production and electricity generation. The framework starts with the energy and electricity portfolio input, and then the identification of production, generation and cooling techniques comes after. The water withdrawal and consumption factors are embedded in the tool represent the life cycle water consumption factors. Therefore, some electricity sources that do not use water for generation and cooling have a water tag. It is because throughout the life cycle of the generation process, such as manufacturing and construction, some water is consumed. This is called indirect electricity water consumption. Some of the produced water in oil and gas production is treated and reused again. Therefore, water reuse in energy production activities decreases the level of consumption, and is an important aspect to consider in the quantification procedure.

By quantifying water usage per energy and electricity source and per type of production and generation, the user is able to unmask the flow of water within the energy portfolio. The ability to quantify the water consumption for every energy activity allows the user to better understand how each element within the energy portfolio scenarios impacts water resources. The tool enables the user to unbundle the water footprint for the whole energy portfolio, allowing the user to better analyze the water flow after performing quantification of each sink.

Water for Energy Production:

The quantification of water consumption for energy production requires only 2 step after the input of the energy production portfolio. This step is the dissection of the energy portfolio into fractions according to the type of production within each source. In other words, for each source, the user has to identify the fraction of energy that was produced from the types of production listed in the tool. The extraction of an energy source is done through multiple techniques, and each technique has a unique water footprint. In addition, the user has to input the percentage of reuse is the water usage for energy production. Let us discuss the techniques, and calculation of water footprints of all energy sources in the tool.

Oil:

The total amount of water consumed in oil production (WEPOL) is a function of type of production ($PTOL_i$) and refining (WROL). The types of oil production included in the tool are primary, and enhanced oil recovery (EOR). Each type has its unique water consumption factor ($WPOL_i$). Therefore, after inserting the total oil production data (EPOL), the user must specify the fractions of production type, so that each production type would match with its water consumption factor, and a better water consumption estimate is achieved. Furthermore, the percentage of water reuse (RUOL) in oil production must be defined. The refining water consumption factor is applied to the total oil production value, as it was assumed that all the oil produced is going through the same refining process. WEPOL is the summation of the water footprint values of oil production types and refining. Below is the table of oil production types, water consumption factors for production and refining, their respective notations, and the WEPOL equation.

Table 6 Notations and water factors for oil production used in EPAT

	i	**$PTOL_i$**	**$WPOL_i$**	**WROL**
Oil (OL)	1	Primary	1	7
	2	EOR	91	

$$WEPOL = EPOL \times [\sum_{i=1}^{2}(PTOL_i \times WPOL_i)(1 - RUOL) + WROL]$$

Natural Gas:

Two types of natural gas production ($PTNG_i$) were considered in the tool, conventional and unconventional, and each technique has an associated water footprint **(**$WPNG_i$). The total natural gas production data (EPNG) is then split in ratios, and then multiplied with its water consumption tag. Also, the percentage of water reuse (RUNG) in natural gas production must be inputted. The water consumed for refining natural gas is obtained by multiplying the total natural gas production value by the water consumption factor for refining (WRNG), after assuming the same refining procedure for all natural gas produced. Shown below is a table displaying natural gas production types, water consumption factors for production and refining, their respective notations, and the equation used to calculate the total water consumed for natural gas production (WEPNG).

Table 7 Notations and water factors for natural gas production used in EPAT

Natural Gas (NG)	**i**	**$PTNG_i$**	**$WPNG_i$**	**WRNG**
	1	Conventional	0.11	2
	2	Unconventional	3	

$$WEPNG = EPNG \times [\sum_{i=1}^{2}(PTNG_i \times WPNG_i)(1 - RUNG) + WRNG]$$

Coal:

A single technique of production was considered for coal production in the tool. The technique (PTCO) is a mix of surface and underground mining, and its water consumption factor (WPCO) reflects the average of both techniques. The percentage of water reuse (RUCO) in coal production must be specified to reflect any current water conservation. Similarly, a uniform water consumption factor for refining (WRCO) is assumed to the total coal produced. Then, the total water consumed for coal production and refining (WEPCO) is the multiplication of the total coal energy produced by water factors.

Table 8 Notations and water factors for coal production used in EPAT

	PTCO	WPCO	WRCO
Coal (CO)	Avg. Surf. & Undgrnd.	**19**	**11**

$WEPCO = EPCO \times (WPCO + WRCO)$

Bioenergy:

For biofuels, the types of ethanol production techniques ($PTBE_i$) considered in the tool are from soy and corn. The bioenergy produced must be split between soy and corn, and each technique has a unique water tag ($WPBE_i$). The water consumption factor for bioenergy covers production and refining. The total water consumed for bioenergy production (WEPBE) is the summation of energy produced by the technique multiplied by the water consumption factor. Below are the notations used in the equation.

Table 9 Notations and water factors for bioenergy used in EPAT

	i	$PTBE_i$	$WPBE_i$
Bioenergy (BE)	1	Ethanol from corn	**198**
	2	Biodiesel from soy	**438**

$WEPBE = EPBE \times \sum_{i=1}^{2}(PTBE_i \times WPBE_i)$

Water for Electricity Generation:

On the other hand, quantification of water usage, consumption and withdrawal, for the electricity generation portfolio require 2 steps after the insertion of the electricity sources data. In the first step, the user has to identify the electricity generation percentage by type of generator for each source. Almost all electricity generation sources have multiple prime movers, and each has its own withdrawal and consumption factors, therefore it is important to split the source generation per type of generator. In the second step, and after forming the generator portfolio within each source, the user has to label the fraction of cooling technology used for each type of generator. Cooling technologies vary within each electricity source and each type of generator, and each cooling technique has a different water consumption dynamic. The embedded water consumption and withdrawal factors take into consideration the current overall efficiency of the generators. These efficiencies are shown in the table below.

Table 10 Fuel type and efficiencies of generator technologies in EPAT

Fuel Type	Generator Technology	Efficiency
Coal	ST	35%
	IGCC	39%
Natural Gas	ST	35%
	CC	54%
	GT	59%
Nuclear	ST	35%

Should an increase in the overall efficiency of a generator occur, the heat being dumped decreases, and therefore fuel input and water use for cooling decreases. Efficiency is inversely proportional to fuel input and water use. Consequently, an increase in efficiency is translated into a decrease in the input fuel, less heat is being dumped and all this finally translated into less water use. Multiplying the fuel input value by the incremental efficiency increase can be done through EPAT.

The electricity generation sources consist of coal, natural gas, nuclear, hydro, wind and solar. Sources are split into two categories: non-renewables, and renewables. The non-renewables (natural gas, coal, nuclear) require cooling, whereas renewables don't.

Electricity coming from nuclear, hydro and wind have only one type of production, which are generic steam, hydro turbine, and wind turbine respectively. Cooling technologies considered are cooling towers, once-through, recirculating reservoirs and dry cooling. Let us discuss the generator types, cooling technologies and calculation of water footprints for all electricity sources in the tool.

Natural Gas:

After the user inserts the total electricity generated from natural gas sources (EGNG), the first step becomes splitting this value by fractions ($GTNU_i$) among the generator types used. The three types of generator types are steam (ST), combined cycle (CC), and gas turbine (GT). These are the main natural gas generator types found in Texas. Each generator i has a n_i cooling technology options. n_i is a constant referring to the number of cooling technologies for generator i. The cooling technology for each generator type i is referred to j notation. The second step is identifying the fraction of electricity produced by generator i using cooling technology j ($CTNU_{ij}$). After splitting the total natural gas electricity generation into the generator types, and each generator type into the cooling technologies, the product of each is multiplied by its associated water consumption factor ($WCNU_{ij}$). Finally, the total water consumed by natural gas electricity generation (WCGNG) is the summation of water consumed by generators with cooling technologies. Below is the table of natural gas generator and cooling types along with their notations. Also, the tool equation used to calculate the total water consumed by natural gas electricity is found below.

Table 11 Notations and water factors for natural gas electricity used in EPAT

	i	**$GTNU_i$**	**j**	**$CTNU_{ij}$**	**$WCNU_{ij}$**	**$WWNU_{ij}$**
Natural Gas (NG)	*1*	**CC**	*1*	**once-through**	28	2,306
			2	**tower**	58	69
			3	**dry**	1	1
			4	**recirc. res.**	67	1,653
	2	**ST**	*1*	**once-through**	82	9,722
			2	**tower**	203	333
	3	**GT**	*1*	**no cooling**	2	2

$$WWGNG = EGNG \times \sum_{i=1}^{3} GTNG_i \sum_{j=1}^{n_i} CTNG_{ij} \times WWNG_{ij}$$

for $\{n_1, n_2, n_3\} = \{4, 2, 1\}$

$$WCGNG = EGNG \times \sum_{i=1}^{3} GTNG_i \sum_{j=1}^{n_i} CTNG_{ij} \times WCNG_{ij}$$

for $\{n_1, n_2, n_3\} = \{4, 2, 1\}$

Coal:

Electricity generated from coal in Texas is mainly through two types, generic steam (ST), and integrated gasification combined cycle (IGCC). Similar the water for natural gas electricity process, the user splits the total coal electric power generated (EGCO) into fractions representing each type ($GTCO_i$). Then, for each generator i, there are n_i number of cooling technologies. The next step becomes further splitting the electricity generated from generator i by type of cooling used ($CTCO_{ij}$). The total coal electricity generated is then multiplied to the product of the fractions, $GTCO_i$ and $CTCO_{ij}$, and then further multiplied with its respective water consumption factor $WCCO_{ij}$. Total water consumed by coal electricity generation (WEGCO) is the summation of products. Below is the table showing coal generator and cooling types along with their notations, and the tool equation used to calculate the total water consumed.

Table 12 Notations and water factors for coal electricity used in EPAT

	i	$GTCO_i$	j	$CTCO_{ij}$	$WCCO_{ij}$	$WWCO_{ij}$
COAL (CO)	*1*	**ST**	*1*	**once-through**	**42**	**9,722**
			2	**tower**	**146**	**181**
			3	**recirc. res.**	**139**	**3,375**
	2	**IGCC**	*1*	**tower**	**89**	**104**

$$WWGCO = EGCO \times \sum_{i=1}^{2} GTCO_i \sum_{j=1}^{n_i} CTCO_{ij} \times WCCO_{ij} \qquad \text{for } \{n_1, n_2\} = \{3, 1\}$$

$$WCGCO = EGCO \times \sum_{i=1}^{2} GTCO_i \sum_{j=1}^{n_i} CTCO_{ij} \times WCCO_{ij} \qquad \text{for } \{n_1, n_2\} = \{$$

<u>*Nuclear:*</u>

Unlike previous sources, the nuclear sources have only 1 type of generator, which is the steam turbine (ST), therefore there is no need for identifying the generator portfolio. Nevertheless, nuclear power uses three types of cooling, so the user must define their fractions ($CTNU_i$) from the total nuclear power generated (EGNU). Each cooling system has a unique water tag ($WCNU_i$). The summation of the products gives the total water consumed in nuclear power generation (WEGNU). The cooling types along with their water tags, notations, and the tool equation used to calculate the total water consumed are shown below.

Table 13 Notations and water factors for nuclear electricity used in EPAT

	GTNU	i	$CTNU_i$	$WCNU_i$	$WWNU_i$
Nuclear (NU)	**ST**	**1**	**once-through**	111	12,778
		2	**recirc.res.**	178	1,889
		3	**tower**	200	306

$$WEGNU = EGNU \times \sum_{i=1}^{3} CTNU_{ij} \times WWNU_{ij}$$

$$WCGNU = EGNU \times \sum_{i=1}^{3} CTNU_{ij} \times WCNU_{ij}$$

Wind:

Wind is a renewable electricity source, and does not directly consumed water throughout its process. Nevertheless, it has a water consumption factor. Water is consumed when manufacturing and constructing the wind turbines, therefore a water consumption factor associated with wind power accounted for. Simply, the total wind power generated (EGWI) is multiplied by the water factor (WCWI) to obtain the total water consumed by wind power (WEGWI). The notations for wind power that were used in the tool calculations are found below.

Table 14 Notations and water factors for wind electricity used in EPAT

	WCWI
Wind (WI)	0.1

$$WEGWI = EGWI \times WCWI$$

Hydro:

Hydropower is a renewable source of electricity, and similar to wind, it has only one type of generator, which is the turbine. Water is consumed in the process of hydroelectric generation through evaporation. Therefore, to quantify the total water consumed by hydropower (WEGHY), the total inserted hydropower generation (EGHY) is multiplied by the water consumption factor (WCHY). The notations for hydropower used in the tool calculations are shown below.

Table 15 Notations and water factors for hydroelectricity used in EPAT

	WCHY
Hydroelectric (HY)	2000

$$WEGHY = EGHY \times WCHY$$

Solar:

Solar is a renewable source of electricity, but unlike wind and hydro, it has two types of generation types embedded in the tool, photovoltaic (PV) and concentrated solar power (CSP). The photovoltaic type does not consume water directly, but similar to the wind turbine, the photovoltaic electricity generation consumed water indirectly. On the other hand, the concentrated solar power type of generation consumes water through both generation and cooling. So, the only step after inserting the total solar power generated (EGSO), is identifying the fraction generated by each type i ($GTSO_i$). Then the generator type fractions are multiplied by their respective water consumption factors ($WCSO_i$). The summation of the product of the fractions and water tags gives the total water consumed by solar power (WEGSO). The notations for solar power used in the tool calculations are shown below.

Table 16 Notations and water factors for solar electricity used in EPAT

	i	$GTSO_i$	$WCSO_i$
Solar (SO)	*1*	**PV**	**0.1**
	2	**CSP**	**250**

$$WEGSO = EGSO \times \sum_{i=1}^{2} GTSO_i \times WCSO_i$$

3.2.1.4. Emissions

Carbon footprint is an environmental cost associated with energy portfolios. Every energy production and electricity generation activity has a carbon footprint. The quantification of the carbon emissions is a must when performing energy planning. In order to ensure a clean future, an understanding of the connection between energy portfolios and carbon emissions is vital. Now, that climate change is becoming a global case, it is posing huge pressures on nations to pay attention to their carbon dioxide emissions coming from the energy portfolios. EPAT, is able to label the carbon emissions of an energy profile. The volume of carbon dioxide discharged depends on the energy source and the activities associated with production and generation. Each energy source has its unique carbon footprint measure that reflects its lifecycle emissions based on its chemical formation and accompanying processes. The emissions produced by each energy and electricity source is simply the product of the total energy and electricity of the source and its respective carbon factor.

The developed tool, EPAT, takes into consideration both direct and indirect contribution of energy portfolios to carbon emissions. Direct contribution is simply through combustion of energy sources. Indirect contribution is the emissions produced by the operational processes. Electricity generation from fossil fuels have a direct impact on the atmosphere since fuel combustion is part of the process. Thus, the carbon footprints of natural gas and coal electricity generation are considered in the calculations. Each fossil fuel electricity source has a unique carbon tag reflecting its direct contribution. The tool assumes that all energy production and some electricity generation activities produce indirect emissions, since no combustion occurs. The carbon footprints for oil, natural gas and coal energy sources reflect the lifecycle emissions produced in the production, extraction, refining and transporting phases. The electricity generation sources that have indirect impact are nuclear, wind, hydro and solar. The nuclear energy carbon footprint in the tool reflects the lifecycle emissions of the process, by considering the emissions produced in mining, milling, refining and disposal. Although some of these activities might not take place in the studied region, but these carbon footprints are somehow imported when generating electricity from nuclear. Wind, hydro and solar are renewable energy sources, and do not directly emit carbon dioxide when generating electricity. Nevertheless, these renewable energy sources have an indirect contribution when manufactured and constructed, therefore, their indirect carbon footprint is accounted for in the tool. Bioenergy is as a renewable energy source, and in fact has a positive effect on the atmosphere by sequestrating the carbon dioxide. However, the production process also has a negative effect on the atmosphere. EPAT considers the indirect emissions of bioenergy. Below are the carbon footprint factor for the energy and electricity sources with their notations, and the equation used to quantify the carbon dioxide emissions.

Carbon Footprint of Energy Production

Table 17 Notations and carbon footprints of energy sources used in EPAT

Energy Source	Notation	Carbon Footprint (g CO_2/GJ)
Oil	CPOL	9,778
Natural Gas	CPNG	32,694
Coal	CPCO	8,889
Bioenergy	CPBE	36,000

$$CEP = EPOL \times CPOL + EPNG \times CPNG + EPCO \times CPCO + EPBE \times CPBE$$

Carbon Footprint of Electricity Generation

Table 18 Notations and carbon footprints of electricity sources used in EPAT

Electricity Source	Notation	Carbon Footprint (g CO_2/GJ)
Natural Gas	CGNG	132,750
Coal	CGCO	246,334
Nuclear	CGNU	5,806
Wind	CGWI	8,194
Hydro	CGHY	3,139
Solar	CGSO	14,833

$$CEG = EGNG \times CGNG + EGCO \times CGCO + EGNU \times CGNU + EGWI \times CGWI + EGHY \times CGHY + EGSO \times CGSO$$

3.2.1.5. Land

Energy production and electricity generation take up a lot of land. Every constituent of the energy portfolio requires a dedication of a piece of land. Land availability is a constraint for energy portfolios. Land might sometimes be considered as a more crucial aspect in energy planning than water. Therefore, the customization of an energy portfolio is directly related to the available land. Land is sometimes introduced as an ecological cost accompanying the energy portfolio because every energy activity has an ecological footprint. Moreover, land is often competed for with the agriculture sector. As a result, land mapping and quantification is a condition to any expansion decision. For example, when a policy maker is planning to modify the energy portfolio of the nation, plans are strictly governed by the availability of land.

Energy production occupies immense acres of land. Oil, natural gas, and coal production all demand spaces of land for onsite mining, extraction and refining. Mining for oil and gas nowadays is becoming a major land user with the adoption of horizontal drilling. Coal surface and underground mining also takes up land, and sometimes even deteriorate the original formation. Nevertheless, transportation of energy products through pipeline networks is one of the major land users in the fossil fuel energy sector. Bioenergy is by far the biggest land occupier through crop plantations requiring significant areas of land.

Electricity generation also demands substantial lands. Land occupation in electricity generation is either through siting and construction of fossil fuel power plants, or through the development of renewable energy farms and sites. Renewable energy require much more land for electricity generation that conventional fossil fuel sources. Building on the discussed ideas, identifying areas of land to be dedicated for energy production and electricity generation while causing ecological, economic and social harm is a major challenge facing both the policy makers and the energy sector.

The land aspect is present in EPAT. The tool quantifies the land demand for the proposed energy portfolio scenario. Every energy production source has a respective land footprint, and similarly for electricity generation.

The land factors embedded in the tool consider the whole lifecycle of the energy and electricity sources. The land factors used in the calculations, along with the equation are shown below.

Land for Energy Production:

Table 19 Notations and land use factors of energy sources used in EPAT

Energy sources	**Notation**	**Land Transformation (m^2/GJ)**
Oil	LPOL	21
Natural Gas	LPNG	31
Coal	LPCO	83
Bioenergy	LPBE	120

$$LEP = EPOL \times LPOL + EPNG \times LPNG + EPCO \times LPCO + EPBE \times LPBE$$

Land for Electricity Generation:

Table 20 Notations and land use factors of electricity sources used in EPAT

Electricity sources	Notation	Land Transformation (m^2/GJ)
Natural Gas	LGNG	2
Coal	LGCO	3
Nuclear	LGNU	13
Wind	LGWI	286
Hydro	LGHY	2,778
Solar	LGSO	115

$$LEG = EGNG \times LGNG + EGCO \times LGCO + EGNU \times LGNU + EGWI \times LGWI + EGHY \times LGHY + EGSO \times LGSO$$

3.2.1.6. Economics

Cost is a major parameter to consider while investigating energy portfolios. The economics are of great interest to policy makers, industry and citizens, for it is the most common method to assessing energy scenarios. The cost of energy varies around the world, depending on the geographic location, technology and the global economy. It energy is neither constant nor independent of externalities. The total cost of energy production is a function of technology, production costs, capital spending, operational cost, subsidies and gross tax. Each component of the total cost of production varies from one area to another, even within the single nation, state and city. Whether producing a barrel of oil from wells or generating a kWh from coal power plants, there is an associated cost. Most nations produce energy to reach self-sufficiency and meet the energy demands of its population and economy. Yet, some nations export energy and make a business out of it. Some policy makers favor the maximization of profit over natural resource conservation, arguing that revenue can be considered as a societal and economic label.

High revenues translate into more jobs, which translates into societal benefit. It is then where financial profit, environmental preservation, cost reduction, and social benefit clash all together.

Unfortunately, obtaining the exact cost of energy production is extremely difficult for a couple of reasons. The first reason is that companies often merge the costs of oil and gas production together in a single total cost. Even though companies split the production data in their report, yet do not separate the costs of oil production from those of natural gas. Bundling costs together masks the individual energy cost of oil and gas. The second reason is that the cost of energy production is complex, as it is a combination of multiple financial and economic factor. Therefore, for energy production, the spot price of energy sources will be used as an economic measure. What is important here in the research is not the exact magnitude change, but in fact the direction of the change. In energy production, the cost of production rises with the price of selling. From an economic standpoint, if the price of energy rises, then more energy is being produced taking advantage of the profitability. On the other hand, if the price of energy is low, then the cost of production will decrease due to the low demand on unprofitable production. Therefore, for energy production, the tool uses the energy price as a measure of the economics of the energy production portfolio. The revenues of the energy production portfolio will be quantified as a function of the spot prices. For coal production, the spot price of lignite coal was considered, by assuming all coal production in Texas give lignite coal. Whereas for bioenergy, for simplicity, it was assumed that bioenergy refers to ethanol, therefore the spot price of ethanol was considered.

Similarly, for electricity generation, the real cost for any electricity generating system is difficult to acquire from the normally accessible information. Cost information for old technologies that have significant historic data are available, such as conventional coal power plants, generic nuclear power plants, and old renewable energy technologies. New technologies have not been operating long enough to formulate costs covering their life-span from operational and maintenance costs. These new technologies include the natural gas combined cycle, modern nuclear power plants, and emerging renewable energy technologies. Furthermore, the accessible cost data of the new technologies does not reflect the lifecycle cost. Thus, the costs of generation adopted by the tool represent the average of old and new generation costs.

The economic parameter in EPAT considers the $ price/GJ for energy produced, and $ cost/GJ for electricity generation. The framework is simplified by calculating revenue for energy production, and cost for electricity generation. These two parameters represent the economic aspect of the portfolio. Below are the spot prices for energy production, and costs of electricity generation used in EPAT. The notations, and the equations used to quantify the revenue and cost are shown below also.

<u>Revenue from Energy Production</u>

Table 21 Notations and spot prices energy sources used in EPAT

Energy sources	**Notation**	**Spot Prices**			
Oil	SPOL	50.45	$/Barrel	8.606982489	$/GJ
Natural Gas	SPNG	2.9	$/MMBtu	2.748815166	$/GJ
Coal	SPCO	31.83	$/short tons	1.5487	$/GJ
Ethanol	SPBE	1.49	$/gal	16.81247028	$/GJ

$$REP = EPOL \times SPOL + EPNG \times SPNG + EPCO \times SPCO + EPBE \times SPBE$$

Cost of Electricity Generation

Table 22 Notations and cost of generation of electricity sources used in EPAT

Electricity sources	**Notation**	**Cost of Electricity Generation \$/GJ**
Coal	CECO	1.138
Natural Gas	CENG	1.4167
Nuclear	CENU	0.972
Wind	CEWI	1.194
Hydro	CEHY	0.9167
Solar PV	CESO	2.138

$$\begin{aligned} EGC = {} & EGNG \times CENG + EGCO \times CECO + EGNU \times CENU + EGWI \times CEWI \\ & + EGHY \times CEHY + EGSO \times CESO \end{aligned}$$

3.2.2. EPAT Interface

In the previous sections, we discussed and introduced the EPAT framework, on which the tool structure was built upon. The EPAT framework allows the user to create energy portfolio scenarios through customizing energy production and electricity generation. More specifically, the user can customize the portfolio through:

- Total energy production by source
- Production technique fractions for each energy source
- Water reuse factor for each energy production source
- Total electricity generation by source
- Generation technology fractions for each electricity generation source
- Cooling system fractions for each generator technology

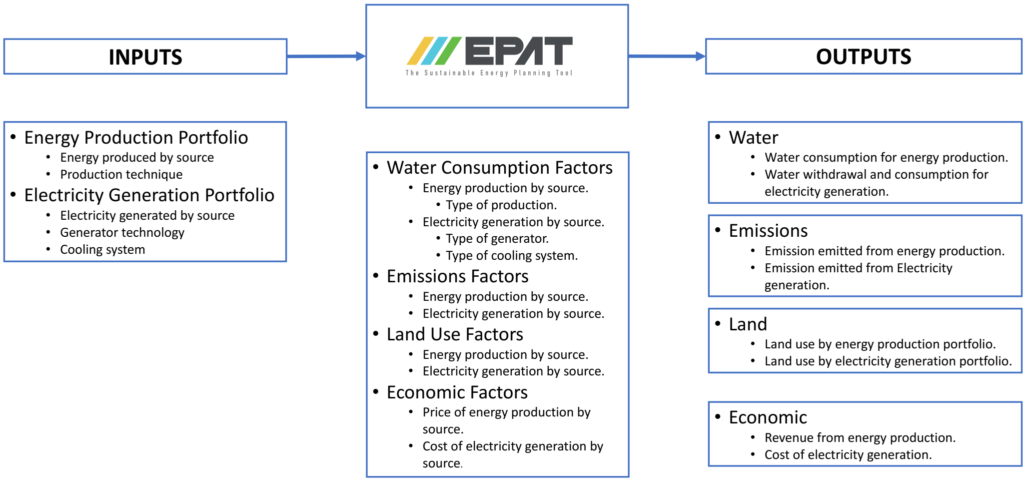


Figure 14 Energy Portfolio Assessment Tool (EPAT) structure

The tool encompasses the characteristics, shown in the above figure, required for the calculation of the outputs. After the input of the customized portfolio, EPAT calculates the following:

- The total water usage (gal)
- The total land occupied (km^2)
- The total carbon emissions (ton CO_2)
- Economics ($)

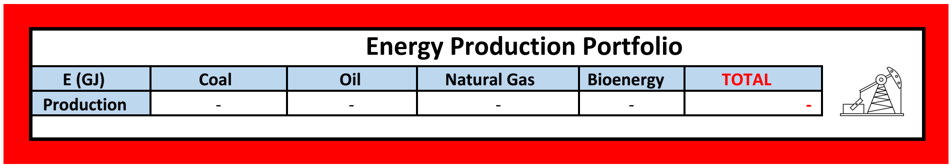
The EPAT interface is simple and straightforward. To create an energy portfolio scenario, the user is required to customize energy production and electricity generation. The input interface is demonstrated below:

3.2.2.1. Energy Production

a. Portfolio: The user is asked to enter the total energy production from the different energy sources listed in the tool. The energy production portfolio is one of the main corner blocks of a scenario. The calculated outputs, and some required inputs are based on the energy production portfolio input. The user has the freedom of altering the energy portfolio, create scenarios and observe the variations.

b. <u>Production Techniques:</u> The user is then asked to enter the percentages of the production type for each energy production source. This step dissects the total energy produced by source per technique used, as each technique has a unique water footprint. The total of production techniques for each source should be equal to 100%, whereas refining is always 100%.

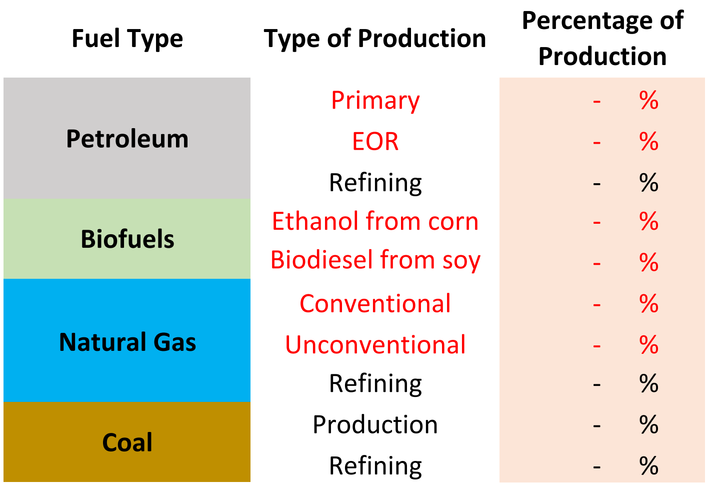
c. <u>Water Reuse:</u> The user is required to input the water reuse percentage for every source in the energy production portfolio. The water reuse factor is a factor of the water conservation initiatives of the scenario. This value cannot exceed 100% for each energy source.



Energy Production Portfolio

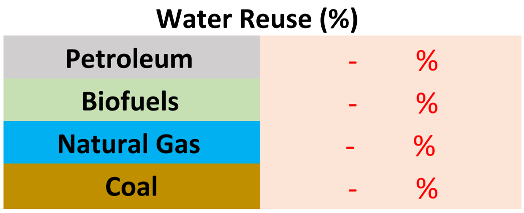
E (GJ)	Coal	Oil	Natural Gas	Bioenergy	TOTAL
Production	-	-	-	-	-

Figure 15 EPAT interface for energy production portfolio data entry



Fuel Type	Type of Production	Percentage of Production
Petroleum	Primary	- %
	EOR	- %
	Refining	- %
Biofuels	Ethanol from corn	- %
	Biodiesel from soy	- %
Natural Gas	Conventional	- %
	Unconventional	- %
	Refining	- %
Coal	Production	- %
	Refining	- %

Figure 16 EPAT interface for fractions of type of energy production



Water Reuse (%)	
Petroleum	- %
Biofuels	- %
Natural Gas	- %
Coal	- %

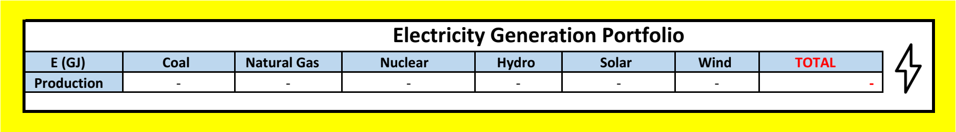
Figure 17 EPAT interface for water reuse percentages

3.2.2.2. Electricity Generation

a. Portfolio**:** The user is asked to enter the total electricity generation from each electricity source listed in the tool. The electricity generation portfolio, similar to the energy production portfolio, is main corner block shaping the outcome of a scenario. The electricity portfolio is a base to further inputs and the final outputs. The user has the freedom of modifying the electricity portfolio to fit a specific region or a desired scenario.

b. Generator Technologies: In this section, the user is required to spread the total electricity generated by each source over the generation technologies listed for each source in the tool. The input is fractional (shown in red), and the total for each electricity source listed should be 100%. Generator technologies vary within the single electricity source, and each generator has a unique water withdrawal/consumption factor. The

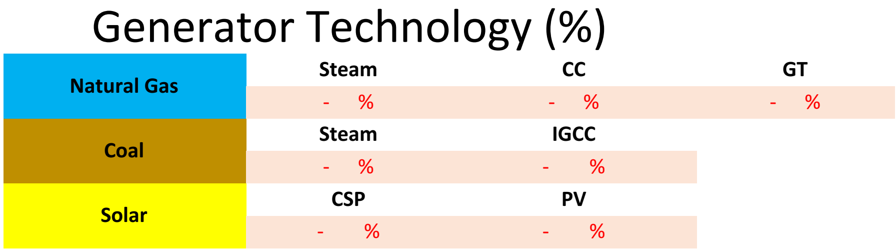
c. <u>Cooling Systems:</u> Cooling systems also vary within the single generator technology. Therefore, the user is required to specify the percentage of cooling technology used for each generator technology that requires cooling. The total of percentages for each generator must be equal to 100%.



Electricity Generation Portfolio

E (GJ)	Coal	Natural Gas	Nuclear	Hydro	Solar	Wind	TOTAL
Production	-	-	-	-	-	-	-

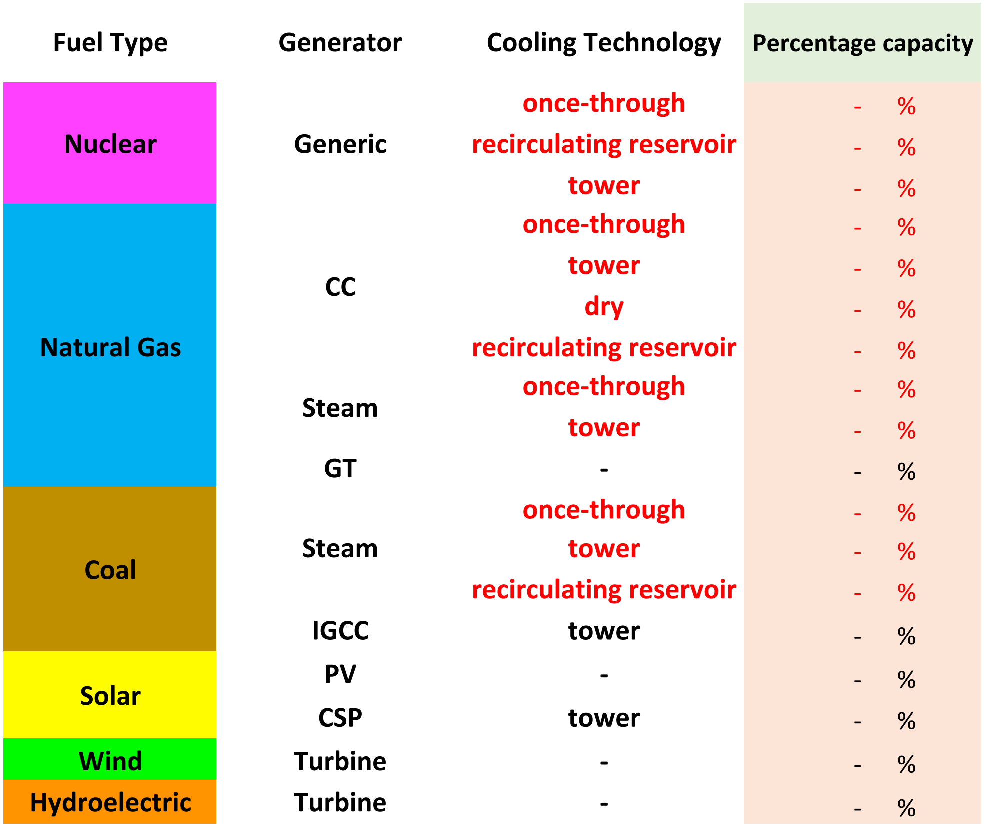
Figure 18 EPAT interface for electricity generation portfolio data entry



Generator Technology (%)

Natural Gas	Steam - %	CC - %	GT - %
Coal	Steam - %	IGCC - %	
Solar	CSP - %	PV - %	

Figure 19 EPAT interface for fractions of type of electricity generator technology

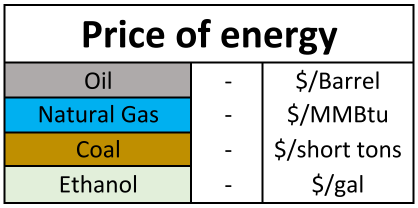


Fuel Type	Generator	Cooling Technology	Percentage capacity
Nuclear	Generic	once-through	- %
		recirculating reservoir	- %
		tower	- %
Natural Gas	CC	once-through	- %
		tower	- %
		dry	- %
		recirculating reservoir	- %
	Steam	once-through	- %
		tower	- %
	GT	-	- %
Coal	Steam	once-through	- %
		tower	- %
		recirculating reservoir	- %
	IGCC	tower	- %
Solar	PV	-	- %
	CSP	tower	- %
Wind	Turbine	-	- %
Hydroelectric	Turbine	-	- %

Figure 20 EPAT interface for defining cooling system fractions for each generator technology

3.2.2.3. Economics

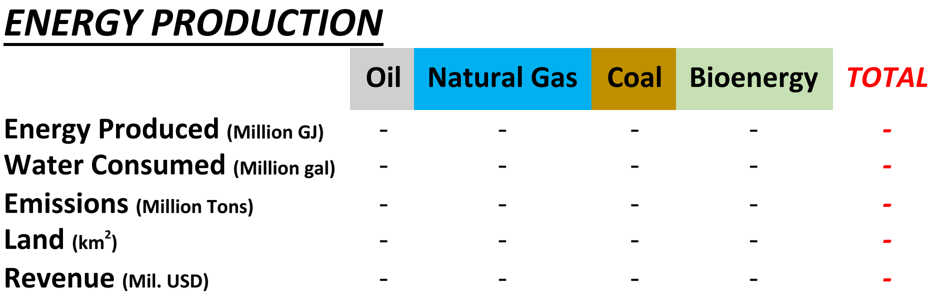
a. Spot Prices: The user must input the latest spot prices of energy resources. The sport prices include the price of a barrel of oil, a million BTU of natural gas, a short ton of coal and a gallon of ethanol. This step is to obtain a realistic revenue output.



Price of energy		
Oil	-	$/Barrel
Natural Gas	-	$/MMBtu
Coal	-	$/short tons
Ethanol	-	$/gal

Figure 21 EPAT interface for energy spot price input

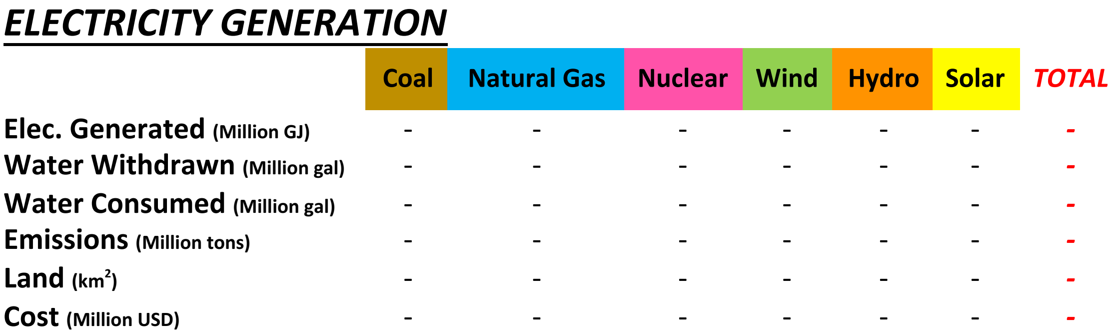
The data input is a dynamic step, as it allows the user to keep modifying the scenario and at the same time quantify and visualize the impact and output variations. After the user completes the data entry and customization of the scenario, the tool directly produces the output in a separate sheet. These output is produced as the following:



ENERGY PRODUCTION

	Oil	Natural Gas	Coal	Bioenergy	*TOTAL*
Energy Produced (Million GJ)	-	-	-	-	-
Water Consumed (Million gal)	-	-	-	-	-
Emissions (Million Tons)	-	-	-	-	-
Land (km^2)	-	-	-	-	-
Revenue (Mil. USD)	-	-	-	-	-

Figure 22 Summary of output results of energy production portfolio in EPAT



ELECTRICITY GENERATION

	Coal	Natural Gas	Nuclear	Wind	Hydro	Solar	*TOTAL*
Elec. Generated (Million GJ)	-	-	-	-	-	-	-
Water Withdrawn (Million gal)	-	-	-	-	-	-	-
Water Consumed (Million gal)	-	-	-	-	-	-	-
Emissions (Million tons)	-	-	-	-	-	-	-
Land (km^2)	-	-	-	-	-	-	-
Cost (Million USD)	-	-	-	-	-	-	-

Figure 23 Summary of output results of electricity generation portfolio in EPAT

CHAPTER IV

TEXAS CASE STUDY

Economic and population growth drive the demand intensity of energy, but do not govern the source and supply of energy (Scott et al. 2011). The source and supply of energy are mainly controlled by energy policies. Energy policies address energy development, production, generation, environmental impacts, and costs. The enacted policies drive the development of energy production, and electricity generation, in the direction of the favorable commodity, through legislations, standards, and regulations. Preference of the outcomes is typically what energy policies are built upon. The choice of preference depends on policy makers. It could be economic, environmental, societal and many others.

The state of Texas represents a perfect case where energy policies have huge effect on the projected energy portfolio. This is because Texas has a diverse energy production and electricity generation portfolios. Texas is the first largest in energy production and consumption, and second largest in population and economy in the United States. Also, the development of conventional and unconventional oil and gas operations, especially in areas dealing with water stress, poses risks and uncertainty amidst increasing economies and populations and limited water availability (Reig et al. 2014). Nonetheless, Texas is approaching a huge water gap in 2070. Therefore, there is no doubt that energy policies will play a huge role in vindicating the future shortage, and steering the direction of energy development in Texas.

The main current policies being practiced include the Renewable Portfolio Standard (RPS), and the Clean Power Plan (CPP). These energy standards and regulations mainly target the electricity generation sector. The RPS mandates the state to provide a minimum amount of generation from renewable energy sources. Each state has a unique RPS target. The renewable energy target for total electricity sales set for Texas was to have an added renewable capacity of 5,000 MW by 2015, and 10,000 MW by 2025. According to the Electric Reliability Council of Texas (ERCOT), Texas has already surpassed its 2025 target in 2009, reaching 13,360 MW (ERCOT 2016). The CPP forces states to reduce carbon dioxide emissions emitted from the burning of fossil fuels. Along with the carbon dioxide reduction, the CPP will extend the tax credits for renewable energy, mainly solar and wind energy. As a result, the RPS policy directly impacts the electricity mix, whereas the CPP has an indirect effect.

In a world of high technological advancements, energy projections on the level of production and generation are crucial when it comes to energy development and natural resource management; especially water and land. The water-energy-food nexus approach will be applied to the whole state of Texas, by assessing the sustainability of its current and projected state energy portfolios. The sustainability assessment of the current and 2030 projected energy and electricity portfolios will be assessed using EPAT. The current and 2030 projected energy portfolios outlined in this research are based on data and projections provided by the EIA. A level of uncertainty exists in every projection process related to many variables. Some of these variables include policies, disruptive technologies, economic activities and climate change.

4.1. Scenarios

The 2016 EIA Annual Energy Outlook projected the energy production for the whole nation. According to the EIA, Texas will play a huge role in the development of oil and gas production, especially the Eagle Ford play. The Eagle Ford area, sited in Texas, is expected to lead the enhancement of production in the coming years. Likewise, the Eagle Ford play is expected to take lead on the continued development of unconventional natural gas production (EIA AEO, 2016). Therefore, acknowledging that Texas will dominate the national oil and gas scene in the coming years, the projected percent change in oil and gas production for the whole nation will be assumed for Texas. Similarly, the projected national production rate for coal and bioenergy will be assumed for Texas. This is because a huge uncertainty exists in energy production projections, due to being heavily dependent on the global price, and price forecast is extremely vague. The EIA report gives a reference projection for the year 2030. The reference projections for oil, natural gas, coal and ethanol production are the most confident projections according to the EIA. Energy production is hugely dependent on the global commodity price, and because to this date, their future is uncertain with current policies, we will only consider one scenario for energy production, which is the reference case. The EIA projection rates were applied to Texas energy production data and results are shown below in Table 23.

Table 23 EIA energy production scenarios in 2015 and 2030

Energy Sources	2015	2030
	Reference	Reference
Oil (trillion barrels)	1.148	0.975
Natural Gas (trillion cubic feet)	8.14	12.1
Coal (million short tons)	35	27
Ethanol (million gallons)	390	371

The 2016 Annual Energy Outlook, by EIA, projects the overall Texas electricity generation to increase by 20 percent from 2015 to 2030. The increase in overall electricity demand, will definitely change the Texas current electricity mix. There are two scenarios: CPP, no CPP. According to the 2016 Annual Energy Outlook, EIA predicts that that EPA's CPP will have a huge effect on the state electricity mix. For example, Coal's projected share of generation depends on the governing policies and regulations. Furthermore, Understanding the water implications of potential electricity generation scenarios is not straight forward. The water savings will significantly rely on the type of generation and cooling systems used by the added or replaced capacity. Therefore, the will have a huge effect when assessing future electricity portfolios; especially for the water-energy nexus. Two factors that have important consequences on the water-energy nexus are the planned retirements and proposed additions to the overall generation capacity, and their associated cooling requirements. Shown below in Table 24, the EIA electricity generation projections for the year 2030.

Table 24 EIA electricity generation scenarios in 2015 and 2030 (billion kWh)

Electricity Sources	**2015**	**2030**	
	Reference	**CPP**	**No CPP**
Natural Gas	214	231	230
Coal	84	73	115
Nuclear	40	40	40
Wind	36	99	60
Other (Solar/Hydro)	3	4	4

Three scenarios will be assessed for sustainability: Reference Case in 2015, CPP with Energy Reference Case 2030, and No CPP with Energy Reference Case.

4.1.1. Scenario 1: Energy Portfolio Reference Case – 2015

Table 25 Scenario 1 - electricity generation portfolio

Electricity Sources (billion kWh)	**2015**	
	Reference	**% Share**
Natural Gas	214	57 %
Coal	84	22 %
Nuclear	40	11 %
Wind	36	9 %
Other (Solar/Hydro)	3	1 %

Table 26 Scenario 1 – energy production portfolio

Energy Sources	**2015**
	Reference
Oil (trillion barrels)	1.148
Natural Gas (trillion cubic feet)	8.14
Coal (million short tons)	35
Ethanol (million gallons)	390

This scenario portrays the state of the art. When projecting energy portfolios and assessing associated impact, it is essential to have a base scenario. The projected scenarios will be compared according to the base scenario, to be able to observe change. The tables above show the energy production and electricity generation portfolios for the year 2015 in Texas. One of the great challenges in energy production is access to data and availability. Often oil and gas data are vague, as companies do not report the full information regarding their production, and often bulk all oil production phases in one total value. This does not let researchers identify the amount of oil produced in each production phase (i.e. primary and EOR). Therefore, as an assumption, and after consulting with experts in the field, that in 2015, 90% of the oil produced in Texas came from primary production, and 10% came from enhanced oil recovery. The total volume of oil produced in Texas in 2015 was 1,148 billion barrels. In 2015, a total around 8 trillion cubic feet of natural gas was produced in the state of Texas. According to the data from the Railroad Commission of Texas (RRC), around 80% of the produced natural gas in Texas is by hydraulic fracturing, and the other 20% are associated natural gas are extracted during oil production (RRC, 2015). Furthermore, coal and bioenergy production (which is mainly ethanol in Texas) are not as popular as oil and gas in Texas. In this, scenario, according to the USDA, almost all ethanol production comes from corn.

Each year and each scenario has a unique electricity portfolio. The electricity demand and generation vary from year to year, and with it vary the generator and cooling techniques. For the year 2015, as shown in the bar chart below (figure 22), 83% of the power plants use a water-based electricity generating and cooling systems. In other words, 51% of power plants operate on the steam cycle, and one third operate on the combined cycles. The remaining 17% power generating plants operate on wind and gas turbines that require negligible volumes of water for cooling (only gas turbines).

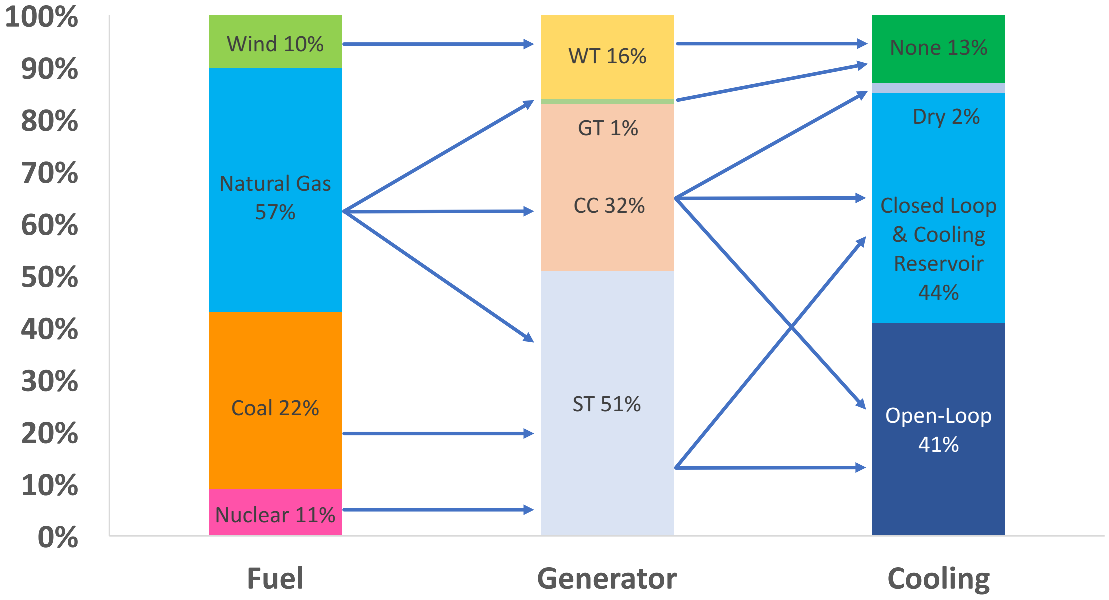


Figure 24 Relationships between fuel, generator, and cooling system for Texas electricity generation portfolio

4.1.2. Scenario 2: CPP with Energy Reference Case – 2030

Table 27 Scenario 2 - electricity generation portfolio

Electricity Sources (billion kWh)	**2030**	
	CPP	**%**
Natural Gas	231	52 %
Coal	73	16 %
Nuclear	40	9 %
Wind	99	25 %
Other (Solar/Hydro)	4	1 %

Table 28 Scenario 2 – energy production portfolio

Energy Sources	**2030**
	Reference
Oil (trillion barrels)	0.975
Natural Gas (trillion cubic feet)	12.1
Coal (million short tons)	27
Ethanol (million gallons)	371

In the CPP case, the retirement of a significant portion coal electricity generation leads to an increased natural gas and renewable energy generation. Texas is projected to decrease its coal-fired generation capacity by 13% by the year 2030 to reach 73 billion kWh. This is not a big surprise, as the state of Texas is not a coal-dependent state, and coal generation has already diminished greatly from sharing generation from 34% to 22% between 2014 and 2015. Although, a decrease in electricity generation from coal would probably lead to a decrease in water requirements, the fate of water savings hinges on the generation types and cooling technologies other sources use, natural gas and renewables. Most units set to retire (i.e. coal) use once-through cooling technologies, whereas new units (i.e. natural gas) are expected to use recirculating cooling technologies. As a result, shifting away from the once-through cooling to recirculating cooling reduces the water withdrawals, but increases increase water consumption. The additional generation capacity from natural gas will come from new combined cycle units with recirculating cooling, with an increase from 214 to 231 billion kWh by 2030. Electricity generation from coal, natural gas and nuclear will still represent a huge portion, almost 70% of total electricity generation in 2030. The renewable energy added capacity will mainly come from wind, and the rest from solar. It is set to supply 25% of the electricity portfolio in 2030 reaching 99 billion kWh. These have extremely low water withdrawal rates that can be considered negligible, but some renewable energy technologies, such as concentrated solar power (CSP) and enhanced geothermal systems (EGS), are considered water-intensive. Nuclear power's electricity generation share is expected to remain constant between 2015 and 2030 supplying 40 billion kWh. Concluding, even with policies encouraging water and environment conservation, water dependent electricity generation power plants will still have a huge impact in the upcoming years amidst vast technological advancements and renewable energy deployment.

The 2016 Annual Energy Outlook projects energy production rates based on the commodity price, prospective technology advancements and anticipated policies. The reference scenario, represents the average scenario of all probable outcomes and extremes. According the outlook, oil production is set to decrease by 15%, coal production set to decrease by 23%, and ethanol production to decrease by 5%, as a reference case by the year 2030. On the other hand, natural gas production is set to increase by 48%. As an assumption based on feedback from experts, EOR activities are set to increase in the future, and around 85% of the oil produced in Texas will come from primary production, and 15% came from enhanced oil recovery.

4.1.3. Scenario 3: No CPP with Energy Reference Case – 2030

Table 29 Scenario 3 - electricity generation portfolio

Electricity Sources (billion kWh)	**2030**	
	No CPP	**%**
Natural Gas	230	51 %
Coal	115	26 %
Nuclear	40	9 %
Wind	60	13 %
Other (Solar/Hydro)	4	1 %

Table 30 Scenario 3 - energy production portfolio

Energy Sources	**2030 Reference**
Oil (trillion barrels)	0.975
Natural Gas (trillion cubic feet)	12.1
Coal (million short tons)	27
Ethanol (million gallons)	371

If the CPP policy gets dropped, or Texas pulls out of the plan, the EIA projected the electricity generation portfolio in that case. Predictably, the electricity generation from coal power plants is will increase significantly, 37%, by the year 2030. This is not a big surprise, as the absence of regulations governing the carbon emissions will pave the way for added coal-fired capacity. Moreover, natural gas electricity generation will increase by 7.5% from by 2030. Similarly, it is assumed that natural gas-fired added capacity are combined cycle power plants with cooling towers. Nuclear power capacity remains constant at 40 billion kWh. Last but not least, renewable energy, the victim, is set to witness a very shy increase compared to the CPP case, only 66%. Electricity generation from coal, natural gas and nuclear will still represent a huge portion, almost 86% of total electricity generation in 2030. Therefore, thermoelectric power plants will remain dominant in the absence of CPP.

Similarly, the same rate projections for oil, natural gas, coal and ethanol production in the previous “CPP with Energy Reference Case - 2030” are applied here in this scenario.

CHAPTER V

RESULTS AND TRADEOFF ANALYSIS

5.1. Results

In this section, the results of the studied scenarios are presented. Every scenario was assessed based on resource requirements and environmental impacts of the energy portfolio. The requirements and impacts assessed are the following:

- Water footprint (Million gal)
- Carbon footprint (Million ton CO_2)
- Land footprint (km^2)
- Revenue from energy production (Million USD)
- Cost of electricity generation (Million USD)

Below are the results of the three studied scenarios, with tables and bar charts showing the resource requirements, and environmental impact of the whole energy portfolio. The results also show the water usage, emissions, land use, cost/revenue of every energy and electricity source as well.

5.1.1. Scenario 1

Scenario 1 is the energy portfolio base case of the year 2015. The scenario depicts the current Texas energy impact situation. The results of this scenarios will be used as a base for comparison and discussion of the 2 cases in the next section.

As you can see in the energy production table below, the most water demanding energy production process is oil production. The amount of water required for oil production in 2015 was almost 200 thousand million gallons to produce 1,148 billion barrels. There are factors that directly affect the total water usage in oil production, and these factors are the production technique, and water reuse. In this scenario, the percentage of production per technique was as follows: 90% from primary production, and 10% from enhanced oil recovery. The split of production was an assumption based on literature review and analyzed production data. The water factors of these two production techniques is nowhere close to one another, as the water used for primary production is almost negligible compared to that of EOR. Therefore, the total amount of water used by oil production is hugely dependent on the percentage of oil produced in the enhanced oil recovery phase. Nonetheless, water reuse is also a factor that affects the water consumption in energy production. An average water reuse percentage, 20%, was set to oil production. The higher the water reuse factor, the less water required and consumed by oil production. On the other hand, natural gas production in Texas has been increasing day by day since the shale revolution, and in 2015, Texas produced 8.14 trillion cubic feet of natural gas. The water used for natural gas production constituted 21% of the total water used by the energy production portfolio, 1,200 thousand million gallons. The total amount of water used by natural gas is also a function of two factors, production technique, and water reuse percentage. Based on gathered data and literature review, it was assumed that 80% of the natural gas being produced in Texas are by unconventional techniques, and the remaining 20% are by conventional methods. The water tag of hydraulic fracturing is much higher than that of conventional production, therefore, the split of total natural gas production directly affects the total water used up by the process. Also, the average 20% water reuse factor was set to natural gas production. Compared to oil and natural gas production, the amount of water consumed by coal and bioenergy is minimal, but if we compare the water consumed per unit energy to those of oil and natural gas, we see a huge difference. The ratio of water consumed per unit energy for oil and natural gas are 29 gal/GJ, 3.5 gal/GJ, 29 gal/GJ and 198 gal/GJ respectively. It is clear now that oil production is the most consuming energy production process, and bioenergy is so far the least water efficient.

Table 31 Scenario 1 - Summary of results for energy production portfolio

ENERGY PRODUCTION

	Oil	**Natural Gas**	**Coal**	**Bioenergy**	***TOTAL***
Energy Prod. (Million GJ)	7,072	9,896	609	46	***17,623***
Water Con. (Million gal)	103,351	34,177	18,257	9,150	***164,934***
Emissions (Million tons)	69	324	5	2	***400***
Land (km^2)	106	208	24	5,545	***5,883***
Revenue (Million USD)	57,917	23,606	1,114	581	***83,218***

Moving forward, emissions emitted throughout the lifecycle of energy production are often disregards. The truth is that compared to the emissions from electricity generation, energy production is almost double, producing 400 tons of CO_2 in 2015. It was found out that natural gas production is the largest carbon dioxide emitter compared to other resources. Energy production not only required water, but also requires land, and throughout the process of energy production, a lot of land are being occupied and transformed. Clearly, the most land demanding energy production process is bioenergy, 5,883 km. Natural gas production is using more land than oil production, almost double. This is not a surprise, due to the new techniques in production, such as horizontal drilling, and the increase in natural gas production the past several years. Last but not least, even amidst declining oil production, it still gives the highest revenue, with 58,000 million dollars, among all other energy resources.

In electricity generation, it is important to split water usage into withdrawal and consumption. In 2015, the total water withdrawn and consumed in Texas were 3,678,518 and 105,815 million gallons respectively. Thermoelectric plants constituted 90% of the whole electricity portfolio, and the plants use coal, natural gas and nuclear as energy sources. Water withdrawal and consumption are directly related to the generator technology and the cooling system implemented. Coal-fired generation withdraws water the most because almost all coal power plants use the steam turbine generator, and the open-loop cooling, but is not the largest water consumer. Coal-fired power plants withdrew 2,074,382 million gallons, and consumed only 1% of what was withdrawn, 22,050 million gallons. Natural gas and nuclear came in second and third respectively in water withdrawal. Natural gas uses three types of generators split as follows: 83% combined cycle, 14% steam and 3% gas turbines. Also, around 80% of the natural gas cooling systems are closed-loop systems. This explains why natural gas is the highest water consumer. Natural gas power plants withdrew and consumed 1,132,536 and 45,511 million gallons respectively. Nuclear power uses a similar generator technology as coal, steam turbines, and mainly closed loop cooling systems. Although the electricity generated from nuclear is almost half of what is generated from coal sources, the amount of water consumed by nuclear power is almost equal to what is consumed by coal. Renewable energy also consume water, especially hydro. Hydroelectric generation withdraws infinite amounts of water, and even though it relies on the natural electro mechanic power generation, significant amount of water is being consumed in the process, mainly by evaporation. Hydro power generated only 6 million GJ in 2015, and consumed 13,000 million gallons. On the other hand, wind and solar electricity generation do not consume water directly in the process, nevertheless, their lifecycle has a water factor. Compared to the other electricity sources, the water consumed by their lifecycle is negligible.

Table 32 Scenario 1 - Summary of results for electricity generation portfolio

ELECTRICITY GENERATION

	Coal	**Natural Gas**	**Nuclear**	**Wind**	**Hydro**	**Solar**	***TOTAL***
Elec. Gen (Million GJ)	302	770	144	130	6	4	***1,357***
Water With. (Million gal)	2.1 x 10^6	1.1 x 10^6	4.7 x 10^5	0	0	0	***3,678,518***
Water Con. (Million gal)	22,050	45,511	25,280	13	12,960	0	***105,815***
Emissions (Million tons)	74	102	1	1	0	0	***179***
Land (km^2)	8	1	2	70	4	1	***85***
Cost (Million USD)	344	1,091	140	155	6	9	***1,745***

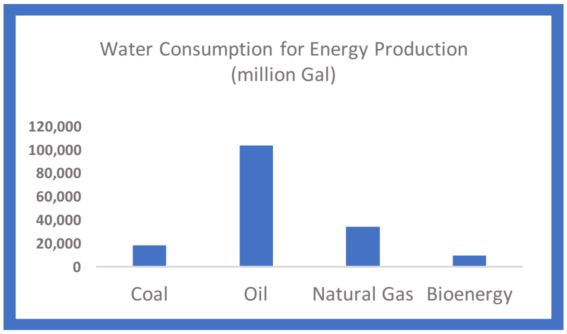


Figure 25 Scenario 1 - water consumption for energy production portfolio

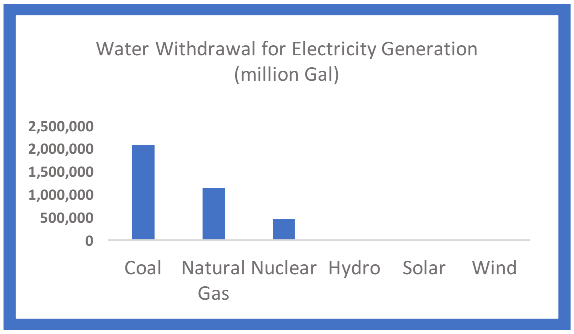


Figure 27 Scenario 1 - water withdrawal for electricity generation portfolio

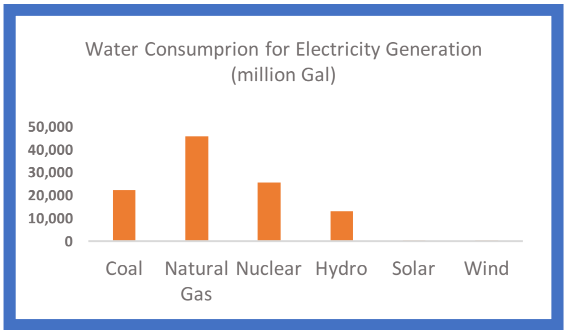
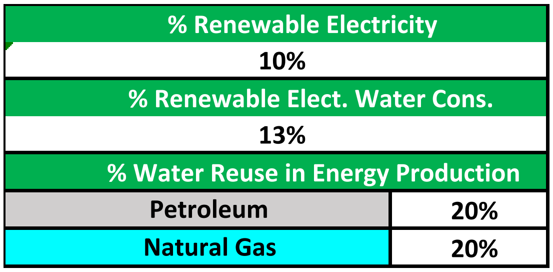


Figure 26 Scenario 1 - water consumption for electricity generation portfolio



% Renewable Electricity	
10%	
% Renewable Elect. Water Cons.	
13%	
% Water Reuse in Energy Production	
Petroleum	**20%**
Natural Gas	**20%**

Figure 28 Scenario 1 - renewable energy and water reuse in energy portfolio

Moreover, emissions are important byproducts in electricity generation. From the table below, it is clear that only coal-fired and natural gas-fired electricity are associated with carbon dioxide emissions. After the quantification, it was found that natural gas power plants in total emit the most carbon dioxide, even though coal is known to be a greater polluter. It is not a surprise because natural gas accounts for 57% of the electricity portfolio. If we compare the amount of carbon dioxide emitted per unit energy between natural gas and coal, we find out that natural gas produces 0.13 tons of carbon dioxide with every GJ, whereas coal produces the double with 0.26 tons of carbon dioxide with every GJ. The impact of coal on carbon emissions is significant, as coal's 20% of the electricity generation portfolio is responsible for 40% of the total emissions. The carbon footprints of nuclear, hydro, wind and solar are negligible as electricity from these sources is generated without any fuel combustion. Nevertheless, they are indirect emitters, as their manufacturing and construction phases have carbon footprints. Land is also a factor in electricity generation, and most specifically when it comes to renewable energy. Clearly, renewable energy require much more land than fossil fuel or nuclear power plants to supply the same capacity. Currently, wind energy accounts for almost 88% of the total land used for electricity generation, 75 km^2. Coal, natural gas, and nuclear also require land for the construction of the power plants, cooling systems and other facilities. Finally, yet importantly, an important factor in electricity generation is the cost of generation. Taking the ratios of cost per unit energy, we conclude that nuclear power has the lowest cost of generation, 0.972 \$/GJ, followed by coal, 1.138 \$/GJ, and wind, 1.194 \$/GJ respectively. As a result, from the clean energy preference, nuclear power and wind energy are cheap sources of electricity compared to natural gas.

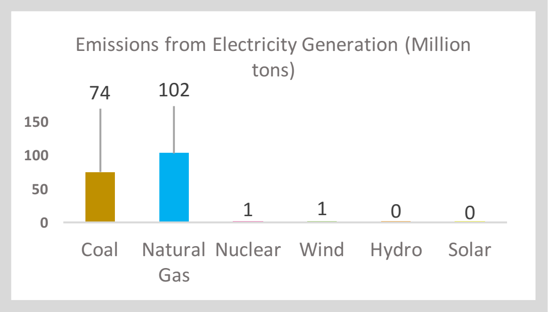


Figure 29 Scenario 1 - emissions for electricity generation portfolio

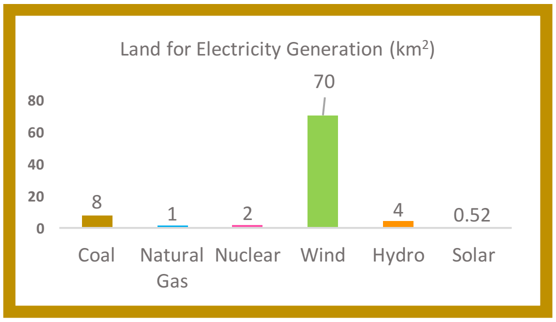


Figure 30 Scenario 1 - land for electricity generation portfolio

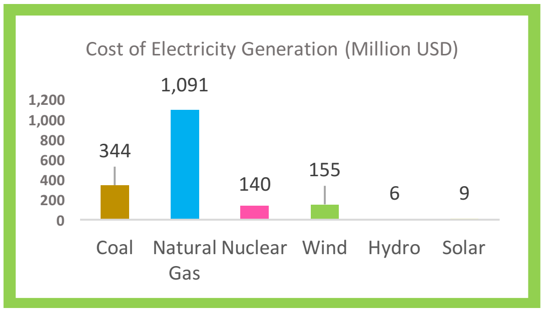


Figure 31 Scenario 1 - cost of electricity generation portfolio

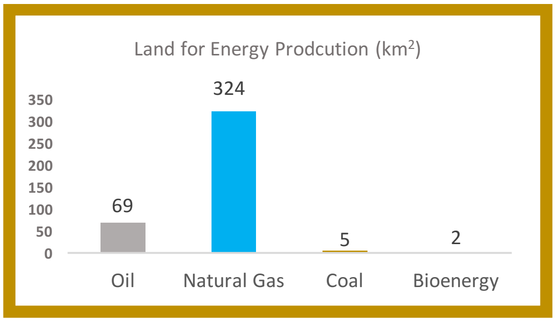


Figure 33 Scenario 1 – land for electricity generation portfolio

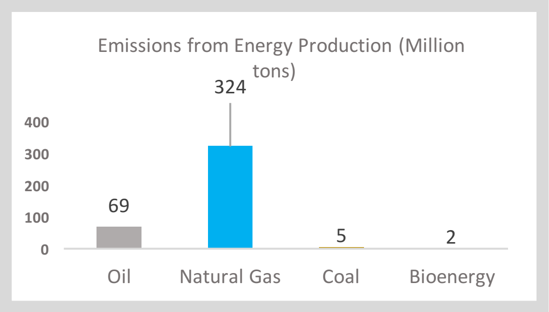


Figure 32 Scenario 1 - emissions for energy production portfolio

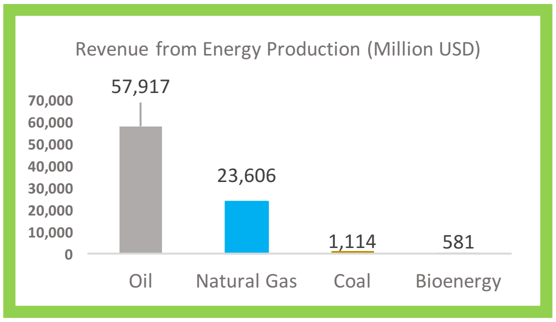


Figure 34 Scenario 1 – Revenue from energy production portfolio

5.1.2. Scenario 2

This scenario is the conservative energy portfolio projection for the year 2030. It considers the reference case for energy production, with an increase in water reuse, and the CPP for electricity generation.

The energy production projections represent the reference case, which according to the EIA is the most probable future scenario given the expected technology advancements, policies and global energy economics. As discussed earlier in the scenarios section, oil, coal and bioenergy production are expected to decrease, yet natural gas production is expected to increase by the year 2030. That decrease in production translates into a decrease in total water consumption, and vice versa. Therefore, water consumed by oil, coal, and bioenergy production decrease, even though EOR activities are expected to increase in the future. The fraction of oil produced through EOR was assumed to be 15% (increasing from 10% in 2015), and the remaining through primary production. On the other hand, the total water consumed by natural gas increased. The decrease in water consumption in oil production, and the increase in water consumption in natural gas production were not proportional to the change in production because the water reuse percentage increased in 2030. The scenario states that by the year 2030 there will be policies and regulations that force oil and gas production activities to increase their water reuse percentage, and 40% was the assumed water reuse percentage for the year 2030.

Table 33 Scenario 2 - Summary of results for energy production portfolio

ENERGY PRODUCTION

	Oil	**Natural Gas**	**Coal**	**Bioenergy**	***TOTAL***
Energy Prod. (Million GJ)	6,011	14,646	456	43	***21,157***
Water Con. (Million gal)	92,477	40,790	13,693	8,601	***155,560***
Emissions (Million tons)	59	479	4	2	***543***
Land (Km^2)	90	308	18	5,213	***5,628***
Revenue (Million USD)	49,189	35,090	859	553	***85,691***

On the environmental side, emissions from oil, coal and bioenergy production will decrease with the decreasing production activities, but emissions resulting from natural gas production activities will increase. Therefore, the total emissions of the energy production portfolio increase by the year 2030, with the natural gas emissions increase being larger than the decrease in all the other energy sources. The total land use by the 2030 energy production portfolio increases with the increasing natural gas production activities. While land use by oil, coal and bioenergy decreases, the increase in natural gas activities dominate the total land used. This is because unconventional gas production is increasing year by year, and in 2030, 90% of the total produced natural gas will be from unconventional sources. Hydraulic fracturing along with horizontal drilling are used to extract the unconventional natural gas. Last but not least, the total revenue resulting from the projected energy portfolio increased by almost 2,000 million dollars, amidst the continuing decrease in oil production. The vast increase in natural gas revenue compensated for the cut downs in revenue from oil production. Nevertheless, the revenues from coal and bioenergy decreased as production decreased.

Table 34 Scenario 2 - Summary of results for electricity generation portfolio

ELECTRICITY GENERATION

	Coal	Natural Gas	Nuclear	Wind	Hydro	Solar	*TOTAL*
Elec. Gen (Million GJ)	263	832	144	356	6	8	*1,609*
Water With. (Million gal)	1.3 x 10^6	5.9 x 10^5	4.7 x 10^6	0	0	0	*2,363,427*
Water Con. (Million gal)	24,638	47,270	25,280	36	12,960	1	*110,184*
Emissions (Million tons)	65	110	1	3	0	0	*179*
Land (km^2)	7	1	2	193	4	1	*207*
Cost (Million USD)	299	1178	140	426	6	16	*2,065*

The CPP full implementation had a huge impact on the Texas electricity portfolio. what is first noticeable is that the coal-fired generation decreased significantly from accounting for 22% of the portfolio in 2015 (302 million GJ) to 16% (263 million GJ) in 2030 with the CPP in action. Natural gas and renewables compensated for the cut down in coal-fired generation. Natural gas capacity increased by 8% to supply 832 million GJ in 2030, whereas the renewable energy share almost tripled supplying 356 million GJ (97%

from wind). Renewable energy from solar sources experience a shy increase, while hydropower capacity remains stable at 6 million GJ since it is restricted by the laws of nature, and Texas already reached maximum hydro capacity.

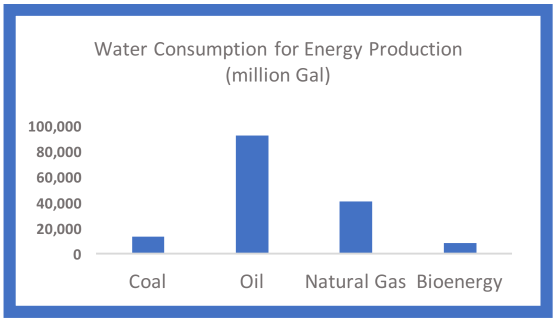


Figure 35 Scenario 2 - water consumption for energy production portfolio

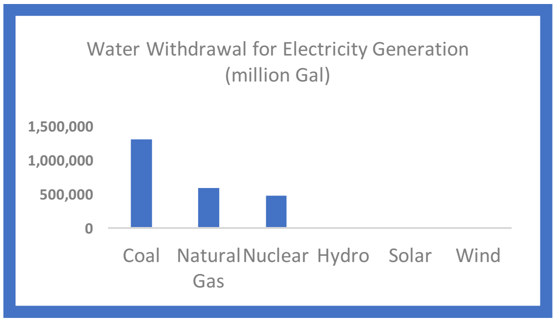


Figure 37 Scenario 2 - water withdrawal for electricity generation portfolio

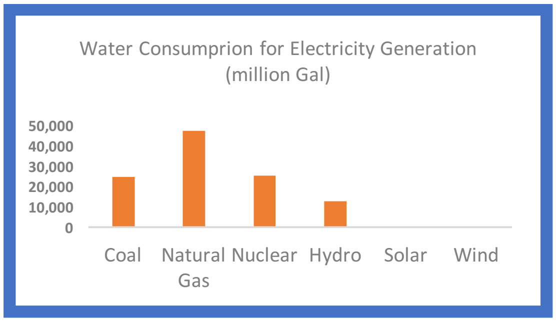
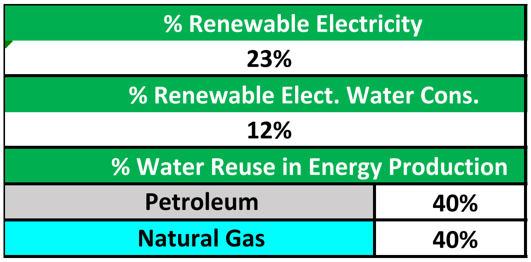


Figure 36 Scenario 2 - water consumption for electricity generation portfolio



% Renewable Electricity	
23%	
% Renewable Elect. Water Cons.	
12%	
% Water Reuse in Energy Production	
Petroleum	**40%**
Natural Gas	**40%**

Figure 38 Scenario 2 - renewable energy and water reuse in energy portfolio

The CPP has a huge effect on the water usage in electricity generation. As the coal-fired capacity decreases, the total water withdrawn by the electricity portfolio decreases. The total water withdrawn by the electricity portfolio decreased by 1,300,000 million gallons. Two main reasons explain this decrease in water withdrawal. First, almost all coal power plants in Texas use the steam cycle for generation, and the open-loop systems for cooling. These two systems are the most water-intensive out of all options. Therefore, the shutdown of plants operating with steam turbines and open-loop cooling system has a positive effect on the water withdrawn (positive being less water is withdrawn). The second reason being that the reduced coal capacity is met by an increase in natural gas and renewable energy. First, the added capacity of natural gas use the combined cycle, which is much more energy and water efficient than the system used in coal power plants. Second, the added capacity of renewable energy is mainly of wind sources, and therefore do not require any water to operate. Third, the cooling systems used in the added natural gas capacity are all closed-loop cooling systems that withdraw around 5% only of what open-loop systems usually withdraw. Coal remains the largest water withdrawing electricity source even with the capacity cut down. Nevertheless, the expected stability in nuclear power supply keeps the water withdrawal rates at a constant assuming the cooling systems of the power plants remain unchanged. Nuclear accounts for one sixth of the natural gas capacity, yet withdraws almost equal volume of water around 810,000 million gallons. Therefore, nuclear power is also an inefficient electricity source when it comes to water withdrawn.

On the other hand, unlike water withdrawal, the total water consumed by the portfolio increased by 5,000 million gallons. The magnitude of change might look small, but as Texas nearing a water gap in 2070, every consumed gallon of water today can have a huge effect. The increase in natural gas generation is the single reason behind the small decrease in total water consumption. This is because almost all natural gas power plants, existing and additional, use the closed-loop cooling. Closed-loop cooling requires less water input, but consumes more water than the open loop systems. While the CPP aims to reduce the total emissions of the electricity portfolio, it is found that it indirectly affects the water consumption rates of the portfolio. The alteration in the electricity portfolio succeeded in reducing emissions and total water withdrawn, but it caused an increase in water consumption as the preference was shifting the portfolio to be cleaner and no more water efficient or less water dependent.

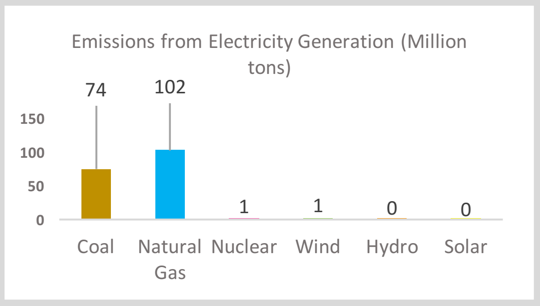


Figure 39 Scenario 2 - emissions for electricity generation portfolio

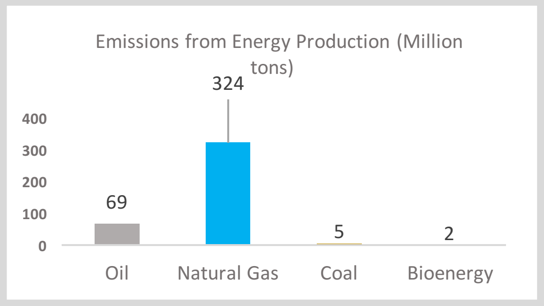


Figure 42 Scenario 2 - emissions for energy production portfolio

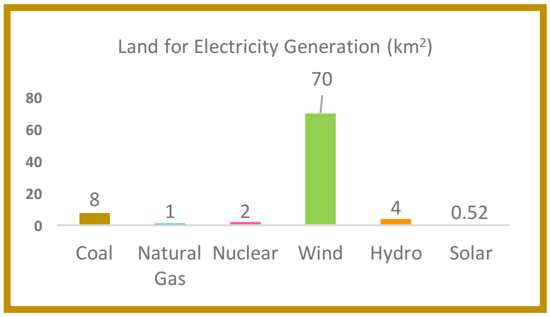


Figure 40 Scenario 2 - land for electricity generation portfolio

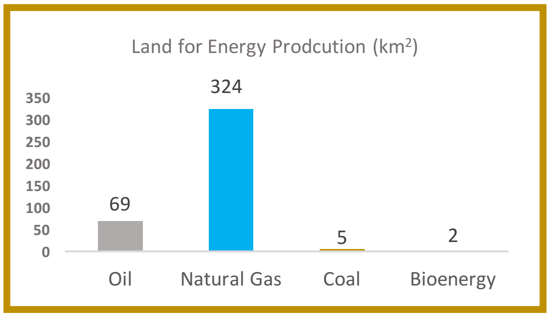


Figure 43 Scenario 2 – land for electricity generation portfolio

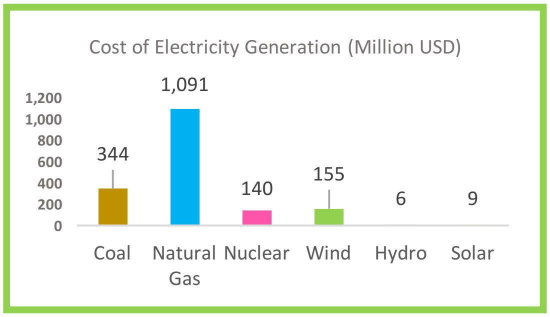


Figure 41 Scenario 2 – cost of electricity generation portfolio

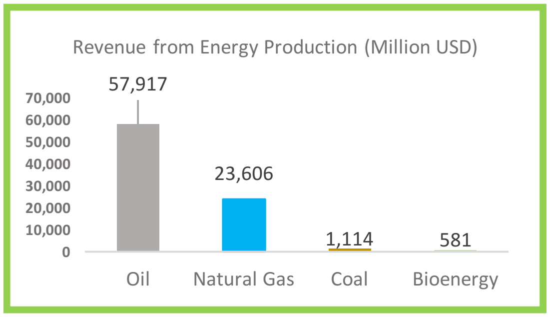


Figure 44 Scenario 2 – Revenue from energy production portfolio

As said earlier, the goal of the CPP is to shift the electricity portfolio towards clean power, and as observed in the table above, the total emissions did not change and remained constant at 179 million tons even with the increase in total electricity generation in 2030. If the calculations accounted for carbon capture, the total emissions in 2030 would have been less than the year 2015. Nonetheless, this is still a significant advancement, as a 20% capacity increase occurred without increasing emissions. The results justify that the CPP succeeded in mitigating the carbon emissions resulting from the electricity portfolio. The CPP indirectly encourages renewable energy deployment, as the policy's end goal is to reduce carbon emissions. As a result, an increase in renewable energy translates into an increase in land use by the electricity portfolio, especially that renewable energy requires huge lands for generation. In 2015, the total land used by the portfolio was 85 km^2 with wind energy responsible for 70 km^2 alone. Renewable energy capacity almost tripled in 2030 with the CPP, and as a result, the total land used by the electricity generation increased from 85 to 207 km^2 with renewable energy accounting for 193 km^2 (mainly wind). Therefore, the CPP requires a lot of land if it is to be fully implemented. This increase in land occupation might lead to clashes with the agriculture sector, as it increases competition on land resources. Last but not least, clean energy and clean environment come at a cost, financial cost. Also, regardless of the CPP, the cost of electricity generation increased by 250 million dollars as the generation capacity increased

5.1.3. Scenario 3

With the new United States administration, speculation started to spread about the EPA dropping the CPP. Texas is the biggest carbon dioxide emitted in the nation, therefore, withdrawing the CPP can lead to serious environmental measures. The scenario also considers the same energy production portfolio discussed in "Scenario 2", but the only difference is that in this anti-conservative scenario, it is assumed that water conserving policies will not be issued by that time, and the current average water reuse factor, 20%, will still be used. Therefore, the only difference in the energy production between the two projected scenarios is the water footprint. In the absence of water policies encouraging water reuse and conservation, with the expected 48% increase in natural gas production by the year 2030, the energy portfolio water consumption increases by 85,000 million gallons. Therefore, in the near future, water conserving policies in energy production must be a priority for policy makers.

Table 35 Scenario 3 - Summary of results for energy production portfolio

ENERGY PRODUCTION

	Oil	**Natural Gas**	**Coal**	**Bioenergy**	***TOTAL***
Energy Prod. (Million GJ)	6,011	14,646	456	43	***21,157***
Water Con. (Million gal)	109,540	54,386	13,693	8,601	***186,220***
Emissions (Million tons)	59	479	4	2	***543***
Land (Km^2)	90	308	18	5,213	***5,628***
Revenue (Million USD)	49,189	35,090	859	553	***85,691***

Let us now discuss how the electricity portfolio will look like in 2030 if the CPP is no longer in action. Unlike the previous scenario, the expected increase in electricity generation is not met by increasing the renewable energy and natural shares. Unsurprisingly, in the absence of regulations against emissions, coal-fired generation increases by 57% to supply 26% of the 2030 electricity portfolio. Natural gas electricity generation also increases by 7.5%. Renewable energy experiences a very shy increase, from supplying 130 million in 2015, to only 216 million GJ in 2030. Renewable energy in this scenario only accounted for 14% of the total electricity generation.

Table 36 Scenario 3 - Summary of results for electricity generation portfolio

ELECTRICITY GENERATION

	Coal	Natural Gas	Nuclear	Wind	Hydro	Solar	*TOTAL*
Elec. Gen (Million GJ)	414	828	144	216	6	8	***1,616***
Water With. (Million gal)	2.1 x 10^6	6.9 x 10^5	4.7 x 10^5	0	0	0	***3,217,270***
Water Con. (Million gal)	38,813	45,614	25,280	22	12,960	1	***122,689***
Emissions (Million tons)	102	110	1	2	0	0	***215***
Land (Km^2)	10	1	2	117	4	1	***135***
Cost (Million USD)	471	1173	140	258	6	16	***2,064***

In this scenario, the absence of regulations targeting emissions, coal power plants increased. The scenario assumes the same generator technology, steam turbines, still being used in coal power plants in the year 2030. The efficiency of coal turbine is one of the lowest available, therefore by increasing coal generation the electricity portfolio in this scenario is not energy efficient. On the other hand, the scenario assumes that all added capacity from coal and natural gas use the closed-loop cooling. Total water withdrawn increases by almost 300,000 million gallons. This is due to the coal-fired generation ramping up. Not only does water withdrawal increase, but also the total water consumption increases. Total water consumed also increased by 17,000 million gallons from 2015. Overall, the electricity generation dependence on water increased in a scenario without the CPP.

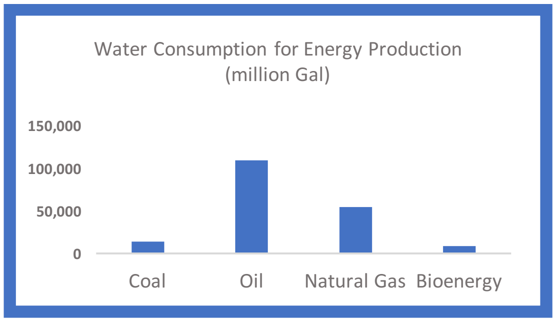


Figure 45 Scenario 3 - water consumption for energy production portfolio

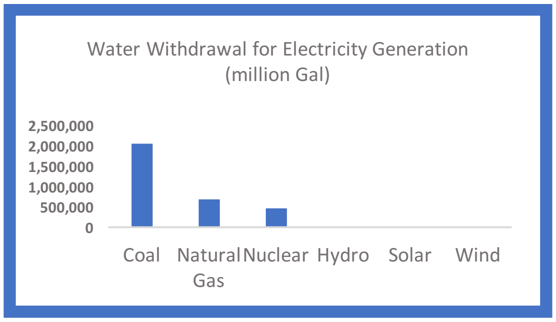


Figure 47 Scenario 3 - water withdrawal for electricity generation portfolio

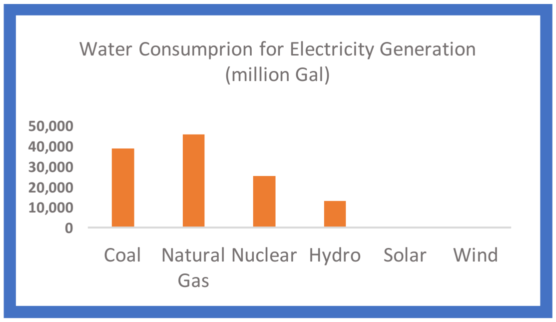
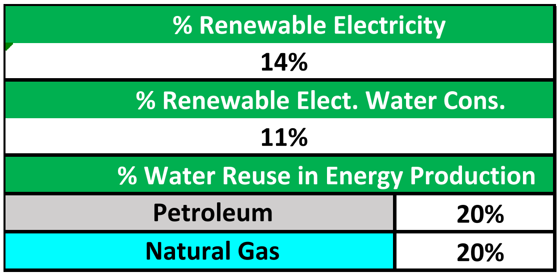


Figure 46 Scenario 3 - water consumption for electricity generation portfolio



% Renewable Electricity	
14%	
% Renewable Elect. Water Cons.	
11%	
% Water Reuse in Energy Production	
Petroleum	**20%**
Natural Gas	**20%**

Figure 48 Scenario 3 - renewable energy and water reuse in energy portfolio

On the environmental side, the contrary to the previous scenario occurs, as the increase in coal-fired generation causes the total emissions to increase. The CPP kept the total emissions at 179 million tons from 2015 to 2030, whereas in this scenario the emissions totaled to 215 million tons. We conclude that the third scenario is neither water efficient, nor environmentally friendly. The total land used by this electricity portfolio is less than scenario 2 because the added capacity of renewable energy is less. Therefore, less land is being used to wind and solar farms. The agriculture sector would favor this scenario, as less land is being taken for energy activities. Finally, surprisingly, with and without the CPP the total costs of electricity generation are almost equal in both scenarios, with this scenario being less by 1 million dollars. The conclusion is that for almost the same cost of generation, this scenario is using and consuming more water, and producing more carbon emissions.

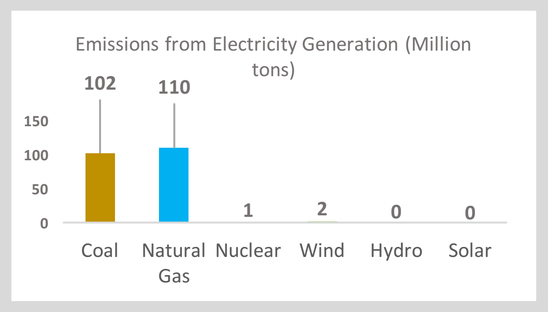


Figure 49 Scenario 3 - emissions for electricity generation portfolio

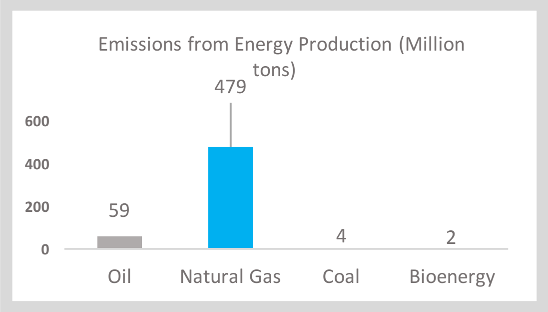


Figure 52 Scenario 3 - emissions for energy production portfolio

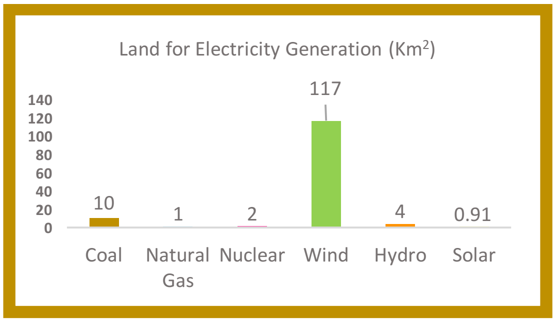


Figure 50 Scenario 3 - land for electricity generation portfolio

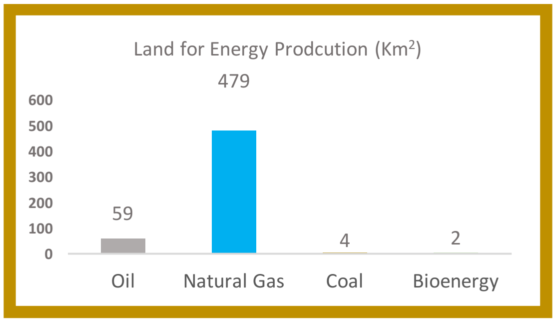


Figure 53 Scenario 3 - land for energy production portfolio

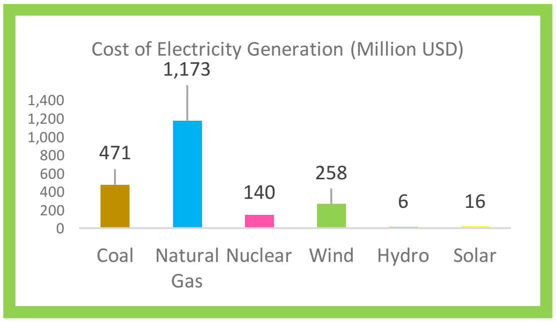


Figure 51 Scenario 3 – cost of electricity generation porfolio

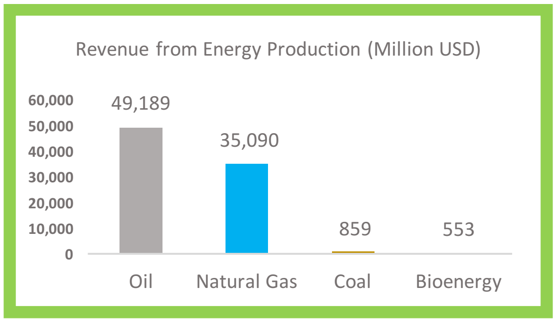


Figure 54 Scenario 3 – Revenue from energy production portfolio

5.2. Tradeoff Analysis

In this section, we analyze the sustainability tradeoffs of future energy portfolios in Texas, and the comparison between the three scenarios is found in the table below.

Table 37 Energy portfolio scenario analysis of outputs

Scenario	1	2	3
Energy Prod. (GJ)	17,623	21,157	21,157
Elec. Gen. (GJ)	1,357	1,609	1,616
Water With. (Elec.) (Mgal)	3,678,518	2,363,427	3,217,270
Total Water Cons. (Mgal)	270,749	265,744	308,909
Total Emissions (Mil Tons)	579	722	758
Total Land (km^2)	5,968	5,835	5,763
Total Energy Revenue (Mil USD)	83,218	85,691	85,691
Total Electricity Cost (Mil USD)	1,745	2,065	2,064

The main focus of the CPP is to decrease the emissions of the electricity portfolio by encouraging the adoption of less polluting and clean energy, such as natural gas and renewables respectively. As the results show in the previous section, the CPP succeeded in decreasing the total emissions of the electricity portfolio by reshaping the generation mix. Nevertheless, the total emissions increased from 2015 to 2030, as the increase in natural gas activities caused a huge emission increase. It has also been observed that energy production emits more pollutants in the atmosphere than electricity generation. Therefore, the focus should also be on energy production regarding emissions, and not only electricity generation.

Nevertheless, as observed in the table of results below, in the presence of the CPP, the total water withdrawn of the whole energy portfolio, energy production and electricity generation, decreased from the year 2015 to 2030. This happened for two main reasons: first being that energy production activities decreased in the projected, and the second is the huge increase in renewables and natural gas electricity generation, and the decrease in coal-fired generation. Of course, cooling systems also react to the shifts in the electricity portfolio. In the second scenario, the number of open-loop cooling systems decrease as coal-fired power plants are substituted by natural gas power plants with closed-loop cooling and renewables. This switch from open-loop to closed loop decreased the total withdrawn water by the electricity portfolio. Also, the total water consumed by the whole energy portfolio decreased by 5,000 million gallons. Nonetheless, while the total amount decreased, the CPP had a negative effect on the water consumed by the electricity portfolio, as it increased. Closed-loop cooling systems consume more water than open-loop cooling, and the CPP has no control on the water use in electricity generation, therefore the added cooling system succeeded in reducing water withdrawal rates, but caused a surge in water consumption. Still, 77% of the electricity portfolio is dependent on water for generation and cooling. Water dependency is not only unsustainable, but also can be considered as a weak spot in the electricity portfolio making the electricity security vulnerable to any serious climatic change, such as droughts.

The third scenario illustrated what would happen if Texas drops the CPP. As you can see, not only the total emissions increased, but also water consumption increased as well. The absence of regulatory actions targeting emissions paved the way to additional coal-fired capacity. As we are sensing the effects of climate change in our everyday lives, visualizing a scenario with no restriction on carbon emissions says how scary the Texas future could be. Texas is now the largest carbon emitter in the United States, therefore regulations, such as the CPP, are a must. Carbon capture and sequestration (CCS) is another way to decrease carbon emissions. Newly built coal-fired power plants are installing CCS systems to reduce carbon dioxide and toxic byproducts. However, CCS can create additional water challenges, since it is capable of doubling the water consumption of power plants.

Every transformation has tradeoffs, and in this case, land is the major tradeoff. Energy production and electricity generation are serious land users. The increase in electricity generation through renewable energy requires a lot of land, and with the CPP in practice, renewable energy is set to witness a glorious surge, especially wind energy. Overall, the expected oil production steep decrease will dominate the land transformation amidst an increase in natural gas production and wind energy generation. As a result, an anticipated oil production decrease leads to a decrease in the total land use in both projected scenario. The third scenario occupies land the least due to wind energy experiencing a shy increase in the absence of the CPP. Also, as bioenergy is projected to hold its current expenditure, land use by bioenergy will remain the same in the year 2030.

Oil production is the energy source with the highest revenue. Yet, the decrease in oil production was met by a huge increase, almost 48%, in natural gas generation by the year 2030. This rise in natural gas production counterbalanced the lost oil money, and translated into 2,000 million dollars increase in scenarios 2 and 3. While the price of ethanol is considered profitable, especially with the current subsidies, production is expected to somehow remain stable. The current energy infrastructure is not ready for an ethanol revolution, although there are technologies now that exist capable of producing ethanol at a really cheap cost. The United States have hit the blend wall, which is 10%, and surpassing that amount requires a huge infrastructure transformation, by retrofitting cars, transportation and distribution systems to accept more ethanol feed.

Cost of electricity generation is also an important aspect to pay attention to when projecting energy portfolios. Of course, an increase in demand on electricity will lead to an increase in the total cost of generation. However, the electricity mix plays a big role in setting up the total costs. As we notice, that the total generation cost of scenario 2 and 3 are almost equivalent. What this tells us is that Texas is able to shift to a cleaner electricity portfolio, without any big difference in cost compared to an electricity mix dominated by fossil fuel and rich in toxic emissions. Nonetheless, with the expected breakthroughs in renewable energy, especially solar and energy storage, the price of electricity per kWh is expected to drop much further once technologies prove their reliability. Currently, Texas is dumping a lot of wind power, due to the huge uncertainty in wind activity forecasts. Had there been efficient and economic energy storage technologies, Texas would not have wasted renewable energy. More renewable energy along with economic and efficient storage can decrease significantly the cost of generation.

Therefore, future conservation and mitigating policies should not limit their focus and target only one system, as this strategy could end up worsening another system at the same time. Also, an increase in production means an increase in revenue, and an increase in land use by energy means fiercer competitions with the agriculture sector. Therefore, priorities should be set on whether to manage land in a sustainable just manner, or favor revenue above all. Stating facts, the agriculture sector is the largest water user in Texas, and its contribution to the Texan economy is far less than what the energy sector brings to the table.

CHAPTER VI

CONCLUSION

Energy portfolios heavily depend on water resources, as water is need for energy production (extraction, processing and refining), and for electricity generation (operation and cooling). Therefore, decision makers must consider the water-energy nexus in development of future energy portfolios to avoid mismanagement of natural resources (minerals, water, land, air…), and to ensure sustainability.

Decision makers are in need of a holistic framework that draws the links between energy and other systems (water, land, environment, finance…) and measure impacts of energy portfolios, to offer a solid foundation for the best sustainable decision making.

EPAT is a tool that enables the policy maker to create different energy portfolio scenarios with various energy and electricity sources, and evaluate its sustainability environmentally and economically.

Texas is a perfect place to study the water-energy nexus and energy portfolio development being the largest energy producer, consumer and electricity generator in the United States. Policies play a big role in setting the direction of energy portfolios towards sustainability. The research assessed projected energy portfolio scenarios for Texas, and while a scenario with CPP decreases the emissions from electricity generation, it increases the water consumption. Therefore, conservation policies should be studied carefully, as they sometimes create problems while solving some. Furthermore, water reuse in energy production is directly related to energy consumption, and is a key in water conservation.

Finally, population and economy growth translate into an increase in demand for energy and water, and meeting these demands in sustainable means is a major challenge. Therefore, we are in need of new forms of decision making that moves from working in the silo systems, to the nexus mentality.

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