University of Oklahoma
School of Chemical, Biological, and Materials Engineering

Oklahoma Energy Planning

Modeling the Future Energy Demands of Oklahoma

Joseph M. Nick Jr.

Vu Le

Table of Contents

List of Figures

Abstract

Oklahoma spends billions of dollars annually on energy consumption and markets for electricity, transportation fuels, and heating utilities are only seeing increased demand and thus increased production. These expansions are resulting in increased carbon dioxide emissions to the environment as well as higher production costs to companies and in turn, higher prices for consumers. New clean sustainable energy production facilities vastly reduce CO_2 emissions, but come at a high cost to Oklahoma's energy companies. On the other hand, existing energy production from the combustion of fossil fuels is far more inexpensive but comes with a different price of its own, environmental emissions. As the state moves farther into the 21st century, an optimum combination between increased sustainable energy production and energy production from fossil fuels must be found. Our project attempts to find this optimum as well as determine what steps should be taken to realize it. What the government needs to do to foster this sustainable energy increase, how much money it will ultimately cost, and ways to attract potential investors for this new energy are all studied in this report.

A model was created using the GAMS optimization package with the CPLEX solver. All three major energy industries were included: electric, transportation fuel, and natural gas heating. The goal of the model is to maximize the net present value of these industries while imposing constraints of required return on investment rates for potential investors, annual percent CO_2 reductions, and job salary increases. We wanted the model to meet the goals by building new wind farms and hydroelectric plants as well as biodiesel and ethanol refineries. In addition, the model is to choose where carbon capture and sequestration technology should be used and how much. Once the model was completed, numerous scenarios were run in order to determine the effect each constraint has on profitability.

A pareto-optimal surface for the net present value as a function of annual percent CO_2 reduction and job salary increase was created from the results of the various scenarios. Job creation, calculated as salaries paid to Oklahoma workers, was shown to have little effect on NPV. However, the CO_2 reduction limit was shown to have a major impact on and an inverse relationship to NPV. It was found that at higher than 2% annual CO_2 reduction, NPV begins to decrease at a faster rate. The model found that the transportation fuel and natural gas industries require little change aside from moderate refinery production increase. In order for the electric industry to meet increased future demand while achieving CO_2 reduction constraints, new clean energy production facilities are needed in the form of wind farms and hydroelectric plants. In addition, existing coal and natural gas plants must see increased carbon capture and sequestration use. Wind and hydroelectric energy sources should increase to 24% and 15% of the total electricity generation by 2030, respectively. Tax breaks of at least 10% of total profit are needed to attract potential investors for the construction of new plants. Electricity price will need to be

increased to a minimum of $0.10 per kilowatt-hour to ensure investors receive a minimum return on investment of 10%.

Objective

The goal of this project is to model Oklahoma's energy industry through the study of past, current, and projected future energy use within the state. In specific, the objective of this project is to predict the optimal yearly energy use in Oklahoma by industry for the next twenty years. A COST model and a PROFIT model have been created that will achieve this objective while seeking to minimize Oklahoma's energy companies' total costs or maximize their net present value, depending on the model. Both models are subjected to constraints of reducing carbon dioxide emissions and increasing job salaries paid to Oklahoma workers by specified levels each and every year. Creating these models required researching all energy produced and consumed within the state as well as the social, environmental, and economic effects this energy use has. Current and past energy data were studied along with predictions about future energy production, cost, supply, and demand to create a model that will plan out the state's energy use until the year 2030. In researching, energy was classified into three distinct categories; electric energy, heating energy, and energy from fuels. Each of these categories required individual research and independent modeling. Once independent modeling had been completed, the individual categories were combined. This combined model was then used to input data and obtain the project's results.

Introduction

Energy is an important issue in today's modern world. It dictates the environmental conditions of a country, controls its economy, and in turn essentially affects the overall prosperity of every region on the planet. Oklahoma is no different when it comes to energy. Oklahoma's energy industry serves to power our homes and cars, heat our churches and schools, as well as create jobs for thousands of Oklahoma men and women every day. However, like the rest of world, Oklahoma's energy industry faces a huge challenge in the 21st century. This challenge is the search to find cleaner, cheaper, and more efficient energy. In 2005 Oklahoma consumed over a quadrillion BTU's of energy and emitted more than 215 billion pounds of carbon dioxide. Despite these astonishing numbers, Oklahoma has the potential to become one of the cleanest and most energy efficient states in the nation. Attributing to this potential is the state's 3-way path to better energy: wind, water, and land. As of 2008, Oklahoma had the 12th largest wind power capacity in the United States. In addition to valuable wind resources, Oklahoma contains more than 78,000 miles of rivers and large streams giving it an enormous opportunity for hydroelectric energy generation[1]. And with more than 75% of Oklahoma classified as farmland, the state has a huge potential for growing crops that can be converted into bio-fuels such a switchgrass and soybeans[2]. Increasing energy production from these sustainable energy sources will decrease carbon dioxide emissions and eventually lower the total cost of energy production. However, developing new technologies and creating sustainable energy will cost incredible amounts of money. For this reason, our project seeks to find the optimum balance between new technology and current energy production methods. This energy optimum will minimize energy costs while reducing emissions to the environment and through the construction of new energy facilities, create jobs and stimulate Oklahoma's economy.

Our project models Oklahoma's energy by taking all current energy sources into account. This includes the supply and demand, current production, future production limits, and costs of all energy produced and consumed in the state. Planning for Oklahoma's energy industry requires studying both its future renewable energy potential and its current energy production. This report makes an in depth study of both of these as well as the potential social, economic, and environmental benefits Oklahoma has to gain from determining the optimal combination of the two. The state is more than ready for tomorrow's energy. The question is, are we?

Overview of Oklahoma's Current Energy

While Oklahoma consumed nearly 1.6 quadrillion BTU's of energy in 2006, it produced more than one and a half times that amount, 2.4 quadrillion BTU's. In 2006 Oklahoma produced more than 5.5 million barrels of oil, 1.7 trillion ft^3 of natural gas, and generated more than 5.4 million megawatt-hours of electricity[3]. For the purpose of this report energy production and consumption will be dealt with in three distinct categories; electricity, fuels, and heating. The electricity data presented in this report consists of coal-fired plants, natural gas fired plants, and petroleum fired plants, hydroelectric plants, and wind farms. Data presented pertaining to fuels consists of the following fuel types; gasoline, diesel, biodiesel, and ethanol[45]. While heating data is given in four distinct categories; residential, commercial, industrial, and plant heating.

Oklahoma Electricity

Natural gas power stations use natural gas as a source of fuel. There are two types of turbines that can be used to provide power to natural gas power stations for electricity production: steam turbines or gas turbines. Steam turbine systems use high temperature and pressure steam to transfer energy to rotating turbine blades, while gas turbines use gas expansion. The turbines are then used to turn electrical generators for production of electricity. For the sake of simplicity, all data associated with natural gas plants was calculated using steam turbine information. This assumption is warranted since most all natural gas plants in Oklahoma are steam turbine operated. Coal-fired plants operate much like natural gas plants but use coal as a fuel source instead of natural gas for power generation.

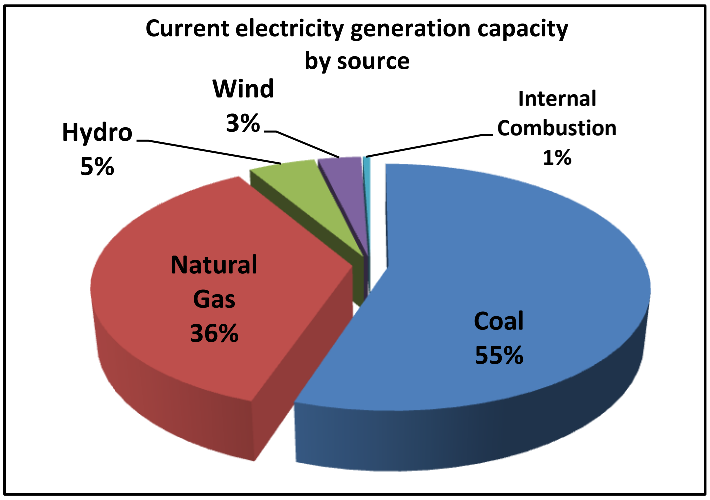


Figure 1. Oklahoma's current electricity generation by source

Nearly 95% of the electricity generated in Oklahoma comes from natural gas and coal-fired plants. The chart at right represents the breakdown of electricity generation in Oklahoma by energy source[3]. As the figure shows, coal-fired plants are the number one source of electricity generation in the state. As coal also has the highest emissions of any energy source in the state, emitting over 5,720 pounds of carbon dioxide for every ton of coal combusted, one can conclude that Oklahoma's current electricity industry is very high in environmental emissions[61]. Table 1 on the next page offers a quick glance at Oklahoma's current electricity production including the CO_2 emissions associated with each energy type. As the table shows, natural gas and coal-fired plants combined emit over 75 billion pounds of CO_2 into the atmosphere every single year. On the other hand, electricity generation from hydroelectric plants and wind farms release nearly zero environmental emissions.

Comparison of coal & natural gas plants to wind & hydroelectric plants			
Fuel Type	Current Capacity (MW)	Emissions (lb. CO_2/MWh)	Approx Total yearly Emissions (lb. CO_2/ yr)
Coal	5,362	2,300	~ 75 billion
Nat. gas	12,883	960	~2.6 billion
Wind	689	negligible	negligible
Hydro	1,110	negligible	negligible

Figure 2. (Table 1) Current coal, natural gas, wind, and hydroelectric plants in Oklahoma

The issue now becomes meeting energy demand. Wind farms and hydroelectric plants in Oklahoma have only 10% of the energy generation capacity of natural gas and coal-fired plants. Compare the number of coal plants, 63, to the number of wind farms, 7, currently producing electricity in Oklahoma.

Although renewable energy sources such as hydroelectric and wind energy appear to represent only a small percentage of current electricity production, this is quickly changing in Oklahoma. For instance, in 2003 zero wind turbines called our state home. Only six years later this number has risen to over 400. These turbines now create over 685 MW of electricity and have the capacity to power approximately two hundred thousand homes. More impressively, these turbines power two hundred thousand homes while producing zero emissions to the environment[4].

Oklahoma Fuel

As of the year 2000 there were over 2.9 million registered cars, trucks, and semi-trucks in the state of Oklahoma[10]. With a population of approximately 3.6 million people, this represents nearly one vehicle on the road for every man, woman, and child living in the state. In 2008 these vehicles used a combined average of over 8 million gallons of gasoline and diesel every single day of the year, resulting in the combustion of over 2.9 trillion gallons of fuel in Oklahoma. As this number illustrates, fulfilling Oklahoma's fuel demand is no easy task. The state's fuel demand is met in a large part by the nine existing oil, ethanol, and biodiesel refineries.

Oklahoma is the home to six major oil refineries with a combined total refining capacity of over 520,000 barrels of oil per day. This is equivalent to approximately 10 million gallons of gasoline and 4 million gallons of diesel fuel produced per day. The table below shows the location and capacity of each of these refineries[5]. Although not all of the fuel produced at these refineries is used within Oklahoma, a great portion of it is.

Refinery	City	Capacity (bbl/d)
Valero	Ardmore	74,700
ConocoPhilips	Ponca City	194,000
Sinclair	Tulsa	70,300
Sunoco	Tulsa	83,200
Wynnewood	Wynnewood	71,700
Ventura Refinery	Thomas	14,000
Total		**520,400**

Figure 3. (Table 2) Oklahoma's current oil refineries

Oklahoma currently contains two biodiesel refineries and one ethanol refinery. These refineries have a combined refining capacity of 115,000 gallons of bio-fuel per day. Although Oklahoma's bio-refineries account for less than one percent of the total fuels produced in the state, this number is both significant and increasing. Its significance stems from the fact that the 8 million gallons of conventional fuel used per day in Oklahoma produce over 160 million pounds of carbon dioxide emissions each day when combusted. This equates to nearly 31 million tons of carbon dioxide released into the atmosphere each year. Bio-fuels help to minimize this number by reducing emissions at refineries, producing less CO_2 when combusted in vehicles, and most importantly by crop CO_2 absorption. The following table illustrates a few of the differences between conventional crude oil derived fuel and bio-fuels[6,7].

Biofuels vs. Petroleum Fuels

Fuel	Feedstock	Capacity (bbl/d)	Refining Emissions (ton CO2/ bbl)	Net Emissions (kg CO2/MJ)
Gasoline	Oil	240,000	0.407	94
Diesel	Oil	200,000	0.102	83
Ethanol	Biomass	130	0.466	-24 (switchgrass)
Biodiesel	Vegetable oil & animal fat	2,600	0.100	~ 43

Figure 4. (Table 3) Comparison of petroleum fuels and bio-fuels

As the table demonstrates, bio-fuels produce fewer emissions by using non-fossil fuel feed stocks, and ethanol produced from switchgrass actually has a negative net CO_2 emission (this will be discussed in further detail later). Also important, bio-fuels allow for the reduced use of foreign oil by producing transportation fuel from resources which are abundant in the United States.

Oklahoma Heating

Heating in Oklahoma can be categorized into four distinct sections; residential, commercial, industrial, and plant heating. The residential sector is defined as use in private dwellings, including apartments, for heating, air-conditioning, cooking, water heating, and other household uses. The commercial sector is use in nonmanufacturing establishments or agencies primarily engaged in the sale of goods or services. Included are such establishments as hotels, restaurants, wholesale and retail stores and other service enterprises; gas used by local, State, and Federal agencies engaged in nonmanufacturing activities. Similarly, the industrial sector is defined as use for heat, power, or chemical feedstock by manufacturing establishments or those engaged in mining or other mineral extractions. Lastly, the plant sector is all heating done within processing plants. Estimates place Oklahoma's heating industry at around 80% natural gas and 15% electricity accomplished[3]. Because heating achieved by electrical energy is covered in the electricity section of the data and project, our focus will remain primarily on heating accomplished by natural gas. In 2007, Oklahoma natural gas consumption was broken down as follows; residential- 17.4%, commercial- 11.9%, industrial- 51.2%, plant- 19.5%[45]. Combined, these four sectors consumed over 343 billion ft^3 or 362 million gigajoules of natural gas and produced over 64 billion pounds of CO_2 in 2007 alone[62, 63].

Oklahoma's Future Energy

The future of Oklahoma's energy is uncertain and only time will tell how and in what ways it will change. For the sake of brevity it suffices to say that all energy production by non-sustainable resources in the state could increase or decrease with time. However, it is logical to believe that this amount of energy production will decrease in the future. Increased study, funding, and research in the area of renewable energy should allow for this decrease to take place. In any case, if energy production by means of non-sustainable resources does increase, there is not likely to be any major changes in the industry. On the other hand, a sharp increase in clean sustainable energy development and production in Oklahoma could lead to many major changes in the energy industry. An overview of the energy produced from clean sustainable energy sources that is currently used in Oklahoma is presented next. This includes an overview of their energy production methods, costs, environmental impacts, and growth potentials in Oklahoma.

Wind Energy

Wind power is created by converting the kinetic energy of the wind into mechanical work used in turning the turbine blades. This mechanical energy is then transferred to an electrical generator. The electrical generators then produce electricity. Wind turbines are capable of creating electrical energy is a variety of wind conditions, ranging from fairly calm to very turbulent. Wind turbines are ideal producers of energy because they produce zero emissions, require little to no maintenance, and once installed can generate electricity for almost no cost.

Most wind turbines in the state are installed on pastures and farmland. Farmers are paid a yearly royalty for turbines installed on their land that varies with wind farm capacity. Typical royalties range from $1,500-$8,000 per megawatt capacity per year. Farmlands that house wind turbines allow Oklahoma farmers to maintain the land's primary farmland use while making royalty money from power companies. Some of the current limitations in wind energy include limited power distribution via inefficient transmission grids, high capital costs, and limited energy storage ability.

Figure 5. A wind farm near Weatherford, Ok

Oklahoma currently has the 12th largest wind energy production capacity in the United States[11]. This energy comes from a relatively small number of turbines, four hundred and twenty. The Oklahoma Department of Commerce estimates that Oklahoma has enough potential wind resources to supply 9% of the entire country's electricity needs if fully realized[8]. While the American Wind Energy Association places Oklahoma in the top eight states for potential wind energy capacity. Nearly all of this land is located in the western part of the state and most of it is available farmland. The following map displays the state's available wind resources. The Oklahoma Wind Power Initiative estimates that the land highlighted in red could potentially sustain up to 10,000 turbines and produce up to 18,000 MW of clean energy[9].

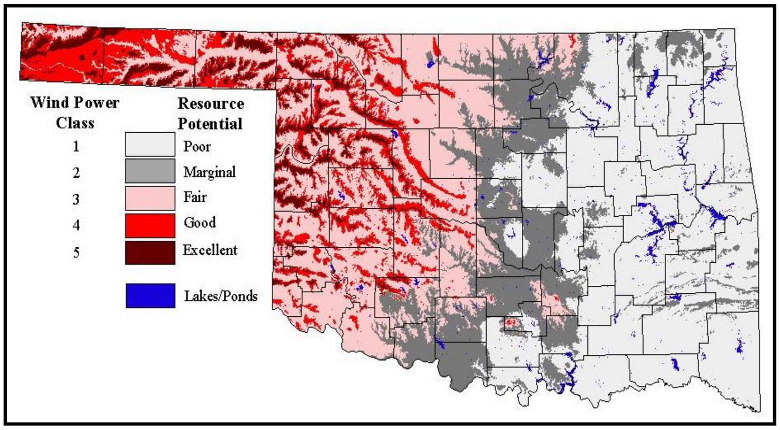


Figure 6. Available wind resources in Oklahoma

As mentioned earlier, a drawback of wind energy is the high associated capital costs. Perhaps the most popular wind turbine today, a 1.5 MW General Electric turbine has a purchasing price of roughly \$1,200,000[34]. By this standard, a typical wind farm containing 100 turbines would cost \$120,000,000. The table below summarizes the energy outputs and required costs associated with a typical Oklahoma wind farm.

Number of Turbines	Turbine Capacity	Total Capacity	Purchasing Cost per turbine	Total cost	Homes powered (approx)
45	1.5 MW	67.5MW	1.2 million	54 million	21,400

Figure 7. (Table 4) Specs of typical Oklahoma wind farm

Wind energy is considered by many to be the technology of the future that is available today. Once installed, it is only a matter of time for wind farms to recover their costly capital investment and start producing energy that is essential 100% free of cost. Oklahoma is beginning to realize this. Our state must make all possible efforts to reach the maximum potential wind capacity and take one step closer to cleaner and cheaper energy.

Hydroelectric Energy

Hydroelectric power stations generate electricity using the force of water falling into turbines and rotating the shaft of the turbines. The potential energy of the water is converted into kinetic energy by rotating the shaft of the turbine. The shaft from the turbine is connected to a generator. The kinetic energy from the shaft turns the electrical generator and produces electricity. Most hydroelectric energy stations of medium to high capacity are built by building a dam on a large river. Water is stored behind the dam in a large reservoir and released onto the turbine propellers through an intake. After passing through the turbine, the water is released back into the river. Some hydroelectric stations, known as run-of-the-river stations, do not require a dam and reservoir in order to generate power. These stations typically have smaller electricity generating capacities.

Oklahoma currently has over 1,100 megawatts of hydroelectric power capacity. This is more than the current wind energy in Oklahoma and nearly 6% of all electric capacity in the state. The picture below is the Pensacola Dam located in Disney, Oklahoma. Situated on the Grand River Valley, the dam has a 120 MW capacity, making it one of the largest hydroelectric power stations in the state[64].

Figure 8. An artist's rendition of Pensacola Dam in Disney, Ok

Hydroelectric power is a very desirable energy source for many reasons. Most importantly, it provides sustainable low emission electricity. By using the potential energy of water as a power source, hydroelectric stations have the ability to provide energy without using any costly feedstock. Also, the efficiency rate of electricity produced from hydro sources is about double compared to fossil fuel plants.

Electricity production from hydroelectric sources within Oklahoma is limited due to the size of the available water resources. Because Oklahoma does not have the resources to sustain large reservoir hydroelectric facilities, most existing plants have small capacities, ranging between 0.5 MW and 120 MW. The facilities with higher capacities utilize small dams to create reservoirs and increase energy potential. However, most of the plants have small capacities and are run-of-the-river type facilities.

Ethanol

Ethanol has many end uses in the world today ranging from alcoholic beverages to antiseptic use. However, its most important use is as a fuel. Ethanol is typically blended with gasoline and combusted in vehicle engines in the same way as pure gasoline. These ethanol “blends” vary in composition and range anywhere between 1% and about 40% ethanol. For instance E85 an 85% gasoline 15% ethanol fuel is sold all throughout the Midwest United States including Oklahoma. Some countries, such as Brazil, produce and sell a 25% ethanol blend fuel. Ethanol burns much like gasoline in vehicles aside from the fact that it produces around 30% less energy per unit volume when burned[31]. This in turn results in a lower fuel efficiency or gas mileage for vehicles. It is for this reason that American’s are skeptical of ethanol fuel use. However, ethanol blended fuels are regularly less expensive than their pure gasoline counter parts. The table below compares the consumer prices of ethanol-blended fuels to pure gasoline.

Fuel Type	**Price** ($/gallon)
Gasoline (87 octane)	$1.94
E85 (85% gasoline 15% ethanol)	$1.70

Figure 9. (Table 5) Comparison of gasoline and ethanol consumer prices

Ethanol can be produced from a variety of different sources by enzymatic breakdown or pyrolysis, fermentation, distillation, and dehydration. The ethanol CO_2 cycle show in figure 5 on the next page illustrates the process by which ethanol is produced as well as how ethanol production is able to achieve net CO_2 emissions.

Corn is currently the leading crop for producing ethanol in the United States. However, the tall cellulosic plant known as switchgrass is the currently most researched and highly praised ethanol production source. Switchgrass is a perennial warm season grass that grows readily in most parts of the mid-west and southern United States[32]. Like corn and other sources, switchgrass is used to produce ethanol by extracting its sugars and fermenting them. However unlike corn, switchgrass is not a food crop in the United States and thus does not have a current limitation for biofuel use.

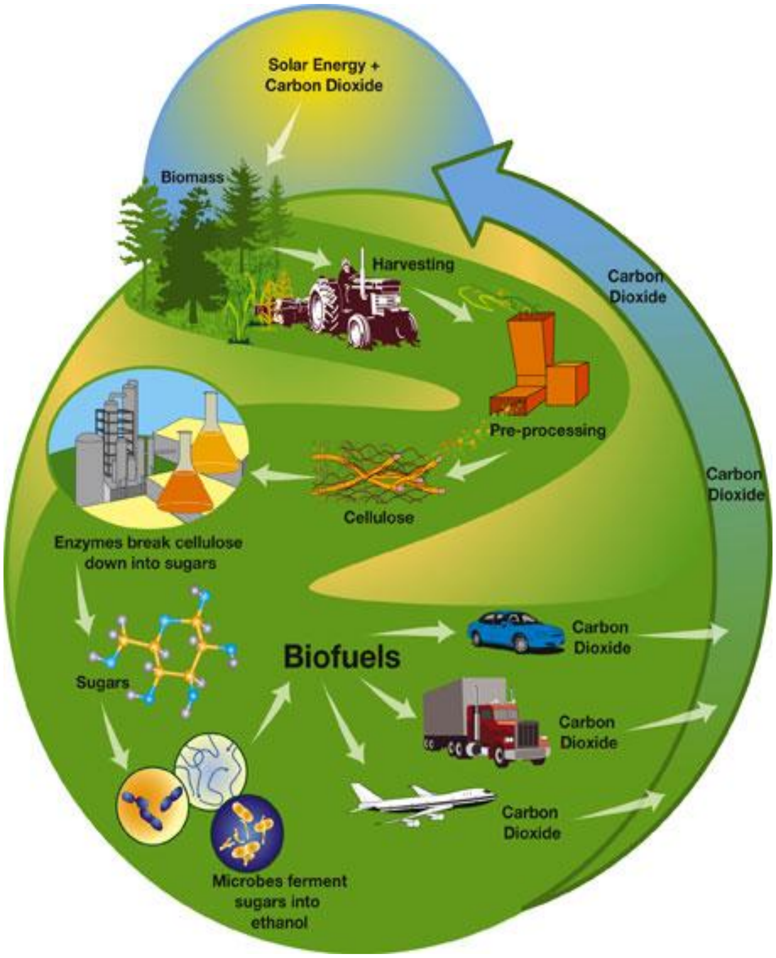


Figure 10. The CO_2 cycle of ethanol production

Ethanol production from switchgrass holds many other advantages over production from corn. Some of these advantages include: reduced fertilizer usage, increased soil sustainability, and increased crop yields. The table below summarizes the comparison between switchgrass and corn.

Our research focuses on Oklahoma's current and projected future capacity to grow switchgrass and produce ethanol from it. Our state currently has an estimated switchgrass farming capacity of 15,000 tons per year. This capacity comes from several different farms and consists of an estimated 2,500 acres of cropland. This switchgrass farmland is located in several regions of the state, with a 1,110 acre farm located in Guymon Oklahoma[36]. Researchers focusing on Oklahoma's ability to increase switchgrass farmland estimate that up to 16,500 acres of land are available to be converted from other crops[37]. With an estimated yield of 6 tons of switchgrass per acre per year, this could mean an increase in capacity to over 110,000 tons per year[38].

	Current Oklahoma Biomass (mil dry tons)	Estimated Ethanol Yield (gal/acre)	Net Energy Gain
Corn	~ 0.8	300-350	21%
Cellulosic crops (switchgrass)	~ 3.3	1100-1200	~ 340%

Figure 11. (Table 6) Comparison of corn and switchgrass ethanol production

Oklahoma currently contains one ethanol production facility located in Burns Flat. This refinery has an annual production capacity of 2 million gallons of ethanol per year. The average U.S. ethanol production facility has a capacity of nearly 50 million gallons of ethanol per year, putting our single plant well below the national average capacity[28]. Increasing our ethanol production requires greatly increasing this capacity. Creating more plants with higher capacities in Oklahoma could mean lower fuel prices, new job creation, and cleaner environmental conditions. Of course, this is no easy task. Building ethanol plants requires great capital and initial operational costs. However, these investments can pay off substantially in the future. The capital cost for building new ethanol production facilities was found from the United States Department of Agriculture and can be approximated at $125 per ton of feed processed. The fixed and variable operating and maintenance costs for new ethanol plants were estimated from the U.S.D.A. in the same way as the capital costs. They were found to be $12 per ton of feed processed and $76 per ton of feed processed, respectively[27].

Biodiesel

Biodiesel is a non-petroleum based diesel fuel that is created from renewable resources such as vegetable oils and fats. Biodiesel consists of long chained alkyl esters that are produced by the transesterification of vegetable oils such as rapeseed oil and soybean oil.

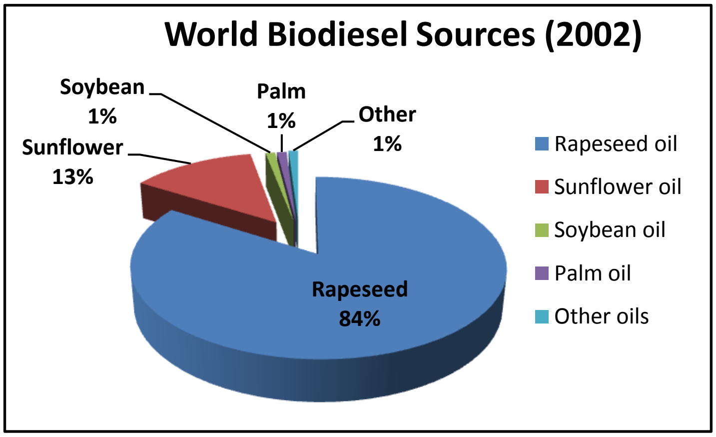


Figure 13. Available world biodiesel sources

Crop	Oil yield per seed mass (kg oil/kg seed)	Oil yields per acre (gal oil/acre)
Rapeseed	37	127
Sesame	50	74
Soybean	14	48
Sunflower	32	102
Mustard seed	35	61
Cotton seed	13	35

Figure 12. (Table 7) Comparison of biodiesel crop properties

Biodiesel can be used in a pure form, B100, or blended with petroleum diesel at various compositions. The most commonly used forms of biodiesel are B20, B5, and B2. These blends represent compositions of 20% biodiesel, 5% biodiesel and 2% biodiesel, respectively. Unlike ethanol-blended gasoline fuels however, biodiesel-blended fuels typically cost more than their pure petroleum counterpart. For this reason biodiesel use in the United States and in Oklahoma is limited. Much research has been done on this new bio-fuel and the future could see the prices of biodiesel blends drop below the price of pure diesel fuel. This price switch could be the result of the increased economy of scale for biodiesel production, agricultural subsidies, or rising oil costs. It has been proven that vehicle engines can be converted to run on purely wasted vegetable oil or “WVO” [12]. However, using this oil as a fuel source is not very efficient and can be difficult to regulate. Similarly, pure biodiesel can be used as a fuel in vehicles. This is not favorable in terms of energy efficiency though. According to the National Renewable Energy Laboratory biodiesel fuel use in vehicles results in decreased power, torque, and fuel efficiency. For instance, use of the blended fuel B20 results in around 1% reduction in the three areas mentioned above. However, in low percentage biodiesel blends such as B5 and lower, the energy reduction is so low that it is unnoticeable[13]. The following table summarizes the prices and heating values of diesel and biodiesel fuels.

Fuel	**Nationwide Average Price** (2008 $/gal)[22]	**Net Heating Value Average** (BTU/gal)[23]
Petroleum Diesel	$3.65	129,500
B5 (5% biodiesel)	$3.84	129,276
B20 (20% biodiesel)	$4.04	127,259
B100 (pure biodiesel)	$4.64	118,296

Figure 14. (Table 8) Comparison of various biodiesel blends

Oklahoma currently has two biodiesel production plants. These plants have a combined production capacity of 109,000 gallons of pure biodiesel per day. As the table 9 below shows, these plants produce biodiesel from many different sources including various vegetable oils and animal fats. The High Plains Bioenergy plant takes pork fat from its parent company Seaboard Foods and creates useable fuel from it. Creating the same amount of petroleum based diesel fuel that these refineries produce per year would take 15,654 barrels of crude oil and produce 5,469 tons of carbon dioxide emissions[16,17].

Increasing Oklahoma’s biodiesel production capacity is something researchers have been studying for several years. Capital costs for newly constructed biodiesel plants in Oklahoma average approximately $280 dollars per ton of feed source. Capital, fixed, and variable operating and maintenance costs were found using a methodology defined in *Biodiesel performance, Costs, and Use*, by Radich. Because the transesterification process of creating biodiesel is virtually the same for both vegetable oil and animal fat feed stocks, the associated costs are the same as well[14]. The fixed operating and maintenance costs as well as the variable operating and maintenance costs as a function of capacity can be seen in the table below.

	Earth Biofuels	**High Plains Bioenergy**
Location:	Durant, Ok	Guymon, Ok
Capacity:	10,000,000 gal / year	30,000,000 gal / year
Feed stocks:	Various vegetable oils	Various vegetable oils and animal fats

Figure 15. (Table 9) Oklahoma's current biodiesel refineries

Associated costs for newly constructed biodiesel plants		
Capital Cost	Variable O&M cost	Fixed O&M cost
$280 / ton of feedstock	$675 / ton of feedstock	$149 / bbl of product

Figure 16. (Table 10) Biodiesel refinery costs

Carbon Capture and Sequestration (CCS)

Carbon capture and storage (CCS) is an approach to mitigating the contribution of fossil fuel emissions to global warming, based on capturing CO_2 from large point sources such as fossil fuel power plants. Carbon capture and storage can be divided into three distinct categories; post-combustion, pre-combustion, and oxy-fuel combustion. In the context of this report, we will be dealing exclusively with post-combustion carbon capture. If may also be noted that in this method, upon capture CO2 is stored underground in geological formation[65]. This type of storage is known as sequestration. Thus in this report CCS shall stand for carbon capture and sequestration rather than storage. Applied to coal-fired power plants, it is estimated the CCS techniques could reduce CO2 emissions to the atmosphere by up to 80%. Capturing CO2 from flue gas and subsequently compressing it in order to send it underground requires enormous amounts of energy. For this reason, it is estimated that CCS applied to a coal-fired power plant could increase fuel consumption by up to 40%[65, 66].

Methodology

Modeling Oklahoma's energy industry from the year 2010 to the year 2030 required the creation of the two mathematical GAMS models that where mentioned previously and will be discussed in further detail later. It also required the compilation of massive amounts of data. A few examples of this data include; the individual capacities of all existing energy creation facilities in the state, the total operating costs of these plants, the CO_2 emissions of these plants, and the job salaries paid to the workers of these plants just to name a few. Much of this information was readily available on government websites such as The Energy Information Administration and The Oklahoma renewable Energy Council. Some of the data was not available and required independent calculation. Examples of required data that had to be independently calculated include; capital cost of new plants, job salaries paid to workers, and several forecasted prices. The purpose of this section is to explain the methodology used in calculating these costs, salaries, and prices.

Capital Costs

The costs associated with energy production plants are numerous and range from the thousands to the billions. For this project we have assumed plant costs to fall into four main categories; capital or expansion costs, operating and maintenance costs, fuel costs, and carbon capture and sequestration costs. Data for the latter three categories was researched and found for each given plant type. Capital and expansion cost data was available but could not be used as easily as the other available data. Because there is a minimum associated cost when building a plant or refinery, a graphical method was used to determine a linear function relating plant capital or expansion costs to capacity.

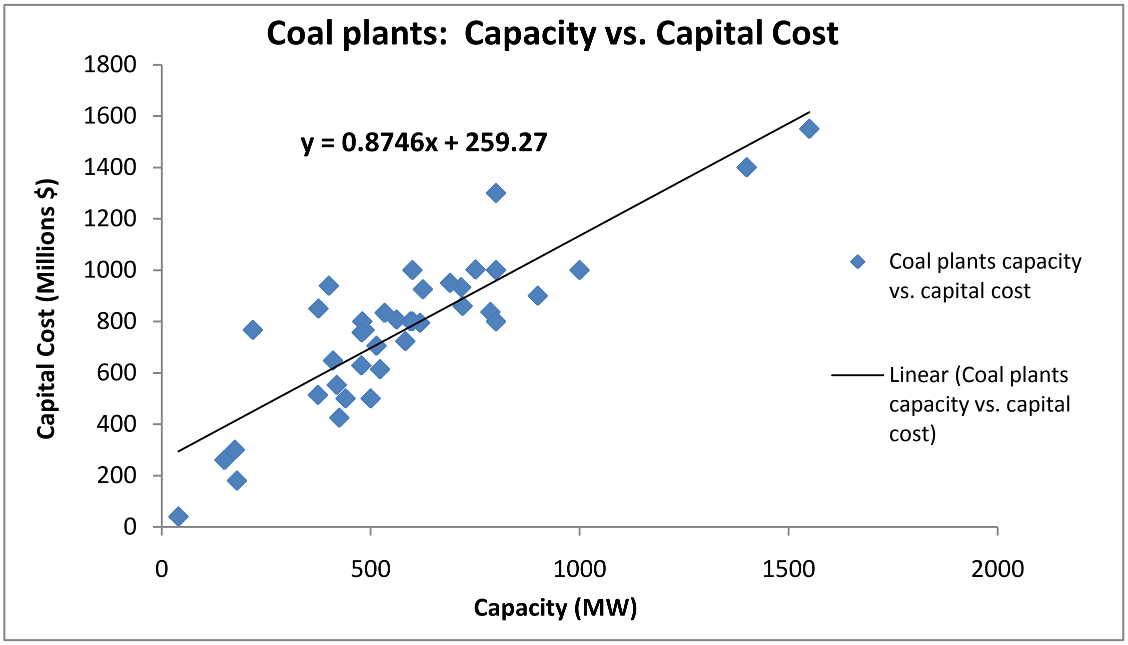


Figure 17. Graphical technique used to find the capital costs of new coal-fired electricity plants based on capacity

The first step in this graphical analysis was to find available data for plant constructions or expansions. This data must include plant type, year of construction, capacity, and total capital cost. All costs where adjusted to reflect present day economic worth. For any given plant type (oil refinery, coal-fired electricity plant, natural gas electricity plant, etc.) a plot of plant capacity versus total capital costs was constructed. Figure 7 shows a plot of this nature.

For all data points, a linear best fit line was added and its' equation determined. The equation shown in figure 18 calculates the capital cost for a new electricity plant based on the desired plant capacity. As the graph shows, there is a minimum building cost, regardless of capacity, of $259 million. Similar plots were constructed for different energy types with similar results obtained.

Job Salaries

Plant construction costs as % of total plant installation cost (total capital)	
Construction Labor Expenses	34%
Construction Material Expenses	66%
Total Expenses (total capital cost)	100%

Figure 18. (Table 11) Recreation of table 6.15 from *Perry's*

One of the constraints imposed on our model was the increase of job salaries paid to Oklahoma workers. In our model, job salaries paid to workers are categorized into construction salaries and operational salaries. Construction salaries are those paid to workers involved in the process of building a new plant or expanding an existing plant. On the other hand, operational salaries are those paid to engineers and operators working at a plant or refinery. As previously mentioned, this data on construction, plant, and refinery workers' wages was not readily available. Construction and operational salaries had to be handled separately and individually calculated. A methodology from *Perry's Chemical Engineer's Handbook* was used to approximate construction salaries. Using Table 11, we estimate the construction wages paid in building a plant or refinery to be approximately 34% of the total capital cost.

Operational salaries were found using *Plant Design*. Figure 8 relates the required operating labor of a chemical refining plant to the plant's capacity. With a known plant capacity figure 8 allows for the calculation of required operating labor in employee hours per day per process step. After finding the operating labor of a plant the plant's typical number of process steps must be found, along with the average worker's salary at that plant type. The average number of process steps for various plant types are presented in table 12 on the following page.

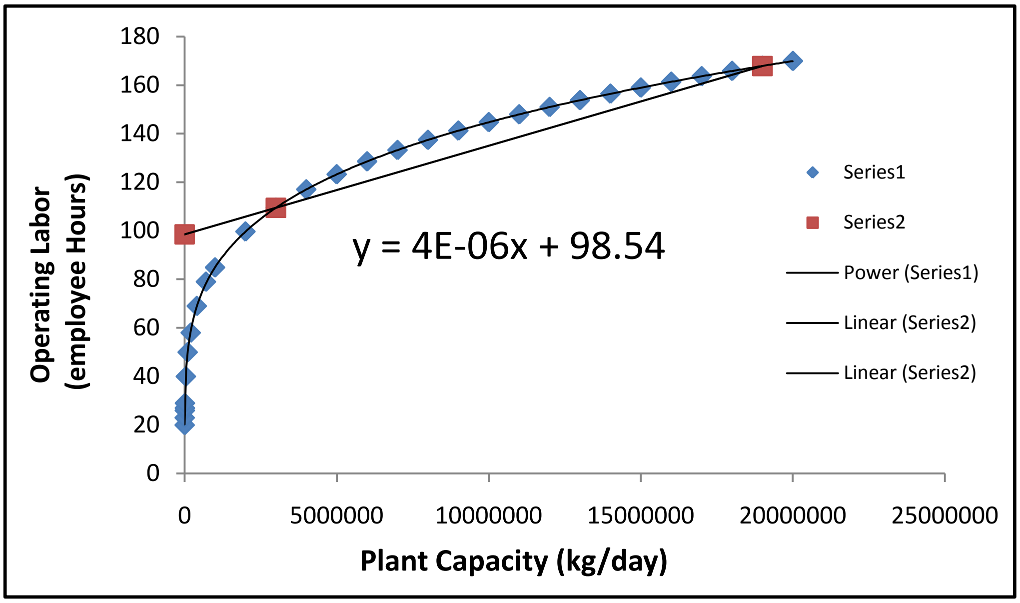


Figure 19. Graph from Plant Design relating plant capacity to required operating labor

For calculating the average refinery and plant worker's salary, table 6-15 from PTW was used. This table means that 65% are operators, while 35% are engineers. Average operator and engineer salaries for Oklahoma refineries in 2008 were found. They are shown in the table 13 below.

Average Oklahoma Refinery Worker Salaries (2008)		
Position	**Experience (yrs)**	**Yearly Salary**
Operator	**n/a**	**$40,000**
Engineer I	**0-1**	**$59,000**
Engineer II	**1-9**	**$74,000**
Engineer III	**10-19**	**$86,000**
Engineer IV	**20+**	**$102,000**

Figure 20. (Table 13) Average Oklahoma refinery worker salaries

Average Process Steps for Various Plant Types	
Oil Refinery	**10**
Biodiesel Refinery	**13**
Ethanol Refinery	**11**
Coal-fired Electricity plant	**7**
Natural gas-fired Electricity Plant	**7**

Figure 21. (Table 14) Average Oklahoma refinery worker salaries

Using the data presented in table 13 along with the plant breakdown assumption of 3 type IV engineers: 10 Engineer III: 20 Engineer II: 30 Engineer I the average Oklahoma salary was calculated to be $24.38.

Algebraic Model

Objective Model

The objective of the model is to maximize the net present value to produce energy from all industry while meeting demand, reducing CO2 emission, and creating jobs. The model was derived from the model created by Hamidreza Mirzaesmaeeli[46]. In his project, he only focused on the minimizing cost for the electricity industry. For our project we added models for the transportation fuels and natural gas heating industries and a profitability model. These various models will be explained further in detail in this section. Below is the objective function of our model.

$$\text{Objective} = \text{maximize}\left(\text{Net Present Value}\right)$$

$$\left(\text{Net Present Value}\right) = \sum_{t}^{n} \frac{(\text{Annual Profit})_t^{\text{Elect}}}{(1+\text{i})^{\text{t}}} + \sum_{t}^{n} \frac{(\text{Annual Profit})_t^{\text{Fuel}}}{(1+\text{i})^{\text{t}}} + \sum_{t}^{n} \frac{(\text{Annual Profit})_t^{\text{Heat}}}{(1+\text{i})^{\text{t}}}$$

Below is a list of the symbols and description used in the model. Similar symbols are used for both the electric and fuel model. There are two units listed here. The first unit refers to the unit used in the electric model and the second unit refers to the fuel model.

Electric Model

Below is a list of the symbols used for the electric model and its description:

Indices

t	Time period (years)
i	individual plant
j	Fuel type (coal/natural gas)

Sets

Elect	Electric plants
New	New power plants or refineries that are built (if not present, symbol pertain to existing plants)

Parameters

F_{ijt}	Fixed operating cost ($)
V_{ijt}	Variable operating cost ($/MWh)
P_{lt}	Annual operation time (hrs)
U_{jt}	Fuel cost for fuel j during period t ($/GJ)
G_{ij}	Heat rate of boiler i using fuel j (GJ/MWh)

S_{ijt}	Capital cost rate of change of new plants (\$ per MWh of capacity)
W_{ijt}	Minimum capital cost of new plants (\$)
ε_{ikt}	Amount of CO_2 removed per generation (ton of CO_2/ MWh)
Q_{ijt}	Cost of carbon capture (\$/ton of CO_2)

Binary Variables

y_{it}	=1 if new power plant is built during period t; otherwise =0
z_{ijt}	= 1 if new power plant is operational during period t; otherwise =0

Continuous Variables

E_{ijt}	Average power generated during period t (MW)
C_{ijt}	The new capacity of new power plants (MW)

Below is a breakdown of the model for the electricity cost:

$$\begin{aligned}(\text{TotalCost})_t^{\text{Electric}} = {} & (\text{FixedOprCost})_t^{\text{Electric}} + (\text{VarOprCost})_t^{\text{Electric}} + (\text{FuelCost})_t^{\text{Electric}} + \\ & (\text{FixedCapitalCost})_t^{\text{New,Electric}} + (\text{FixedOprCost})_t^{\text{New,Electric}} + (\text{VarOprCost})_t^{\text{New,Electric}} + \\ & (\text{FuelCost})_t^{\text{New,Electric}} + (\text{CarbonCaptureCost})_t^{\text{Electric}} + (\text{CarbonCaptureCost})_t^{\text{New,Electric}}\end{aligned}$$

Below is a breakdown of the various costs in more detail:

$$(\text{FixedOprCost})_t^{\text{Elect}} = \sum_i \sum_j F_{ijt}^{Elect}$$

$$(\text{VarOprCost})_t^{\text{Elect}} = \sum_i \sum_j V_{ijt}^{Elect} \hat{E}_{ijt}^{Elect} P_t^{Elect}$$

$$(\text{FuelCost})_t^{\text{Elect}} = \sum_i \sum_j U_{it}^{Elect} G_{ij}^{Elect} \hat{E}_{ijt}^{Elect} P_t^{Elect}$$

$$(\text{FixedCapitalCost})_t^{\text{New,Elect}} = \sum_i \sum_j S_{ijt}^{New,Elect} \hat{C}_{ijt}^{New,Elect} + \hat{y}_{ijt}^{New,Elect} W_{ijt}^{New,Elect}$$

$$(\text{FixedOprCost})_t^{\text{New,Elect}} = \sum_i \sum_j F_{ijt}^{New,Elect} \hat{z}_{ijt}^{New,Elect}$$

$$(\text{VariableOprCost})_t^{\text{New,Elect}} = \sum_i \sum_j V_{ijt}^{New,Elect} \hat{E}_{ijt}^{New,Elect} P_t^{New,Elect}$$

$$(\text{FuelCost})_t^{\text{New,Elect}} = \sum_i \sum_j U_{ijt}^{New,Elect} G_{ij}^{New,Elect} \hat{E}_{ijt}^{New,Elect} P_t^{New,Elect}$$

$$(\mathrm{CarbonCaptureCost})_t^{\mathrm{Electric}} = \sum_i \sum_j Q_{ijt}^{Elect} \varepsilon_{ijt}^{Elect} \hat{E}_{ijt}^{Elect}$$

$$(\mathrm{CarbonCaptureCost})_t^{\mathrm{New,Electric}} = \sum_i \sum_j Q_{ijt}^{New,Elect} \varepsilon_{ijt}^{New,Elect} \hat{E}_{ijt}^{New,Elect}$$

Transportation Fuel Model

Below is a list of the symbols used for the transportation fuel model and its description:

Indices

t	Time period (years)
i	individual plant
j	Fuel type (coal/natural gas)

Sets

Fuel	Transportation Fuel Refineries
New	New power plants or refineries that are built (if absent, symbol pertains to existing refineries)

Parameters

F_{ijt}	Fixed operating cost ($)
V_{ijt}	Variable operating cost ($/barrels of raw material)
P_{lt}	Annual operation time (hrs or days)
U_{jt}	Fuel cost for fuel j during period t ($/barrel or $/ton)
R_{it}	Cost associated with expansion of existing refineries ($/capacity)
S_{ijt}	Capital cost rate of change of new refineries ($ per bbl/day of capacity)
W_{ijt}	Minimum capital cost of new refineries ($)
ε_{ikt}	Amount of CO_2 removed per production (ton of CO_2/ bbl/day)
Q_i	Cost of carbon capture and storage for boiler i ($/ton of CO_2)

Binary Variables

y_{it}	=1 if new refinery is built during period t; otherwise =0
z_{ijt}	= 1 if new refinery is operational during period t; otherwise =0

Continuous Variables

E_{ijlt}	The amt of energy in the product (Btu)
B_{ijlt}	Volume of raw material processed at refineries (bbl/day or tons/day)
C_{ijt}	The capacity of new refineries (bbl/day)

Below is a breakdown of the model for the transportation fuel cost:

$$\begin{aligned}(\mathrm{TotalCost})_t^{\mathrm{Fuel}} = {} & (\mathrm{FixedOprCost})_t^{\mathrm{Fuel}} + (\mathrm{VarOprCost})_t^{\mathrm{Fuel}} + (\mathrm{FuelCost})_t^{\mathrm{Fuel}} + \\ & (\mathrm{CapitalCost})_t^{\mathrm{New,Fuel}} + (\mathrm{ExpansionCost})_t^{\mathrm{New,Fuel}} + (\mathrm{TransportationCost})_t^{\mathrm{New,Fuel}} + \\ & (\mathrm{FixedOprCost})_t^{\mathrm{New,Fuel}} + (\mathrm{VarOprCost})_t^{\mathrm{New,Fuel}} + (\mathrm{FuelCost})_t^{\mathrm{New,Fuel}} + \\ & (\mathrm{CarbonCaptureCost})_t^{\mathrm{Fuel}} + (\mathrm{CarbonCaptureCost})_t^{\mathrm{New,Fuel}}\end{aligned}$$

Below is a breakdown of the various costs:

$$(\mathrm{FixedOprCost})_t^{\mathrm{Fuel}} = \sum_i \sum_j F_{ijt}^{Fuel}$$

$$(\mathrm{VarOprCost})_t^{\mathrm{Fuel}} = \sum_i \sum_j V_{ijt}^{Fuel} \hat{B}_{ijt}^{Fuel} P_t^{Fuel}$$

$$(\mathrm{FuelCost})_t^{\mathrm{Fuel}} = \sum_i \sum_j U_{it}^{Fuel} \hat{B}_{ijt}^{Fuel} P_t^{Fuel}$$

$$(\mathrm{FixedCapitalCost})_t^{\mathrm{New,Fuel}} = \sum_i \sum_j S_{ijt}^{New,Fuel} \hat{C}_{ijt}^{New,Fuel} + \widehat{y}_{ijt}^{New,Fuel} W_{ijt}^{New,Fuel}$$

$$(\mathrm{ExpansionCost})_t^{\mathrm{New,Fuel}} = \sum_{\substack{i=oil\\ refineries}} \sum_{j=oil} S_{ijt}^{New,Fuel} \hat{C}_{ijt}^{New,Fuel} + \widehat{y}_{ijt}^{New,Fuel} W_{ijt}^{New,Fuel}$$

$$(\mathrm{TransportationCost})_t^{\mathrm{Fuel}} = \sum_i \sum_j \left(MilesTravelled\right)_{ij}^{Fuel} \left(TruckFuelCost\right)\left(Mileage\right)\left(TruckCap\right)_{ij}^{Fuel} \hat{B}_{ijt}^{Fuel} P_t^{Fuel}$$

$$(\mathrm{FixedOprCost})_t^{\mathrm{New,Fuel}} = \sum_i \sum_j F_{ijt}^{New,Fuel} \hat{z}_{ijt}^{New,Fuel}$$

$$(\mathrm{VarOprCost})_t^{\mathrm{New,Fuel}} = \sum_i \sum_j V_{it}^{New,Fuel} \hat{B}_{ijt}^{New,Fuel} P_t^{Fuel}$$

$$(\mathrm{FuelCost})_t^{\mathrm{New,Fuel}} = \sum_i \sum_j U_{it}^{Fuel} \hat{B}_{ijt}^{New,Fuel} P_t^{Fuel}$$

$$(\mathrm{TransportationCost})_t^{\mathrm{New,Fuel}} = \sum_i \sum_j \left(MilesTraveled\right)_{ij}^{Fuel} \left(TruckFuelCost\right)\left(Mileage\right)\left(TruckCap\right)_{ij}^{Fuel} \hat{B}_{ijt}^{New,Fuel} P_t^{Fuel}$$

$$(\mathrm{CarbonCaptureCost})_t^{\mathrm{Fuel}} = \sum_i \sum_j Q_{ijt}^{Fuel} \varepsilon_{ijt}^{Fuel} \hat{B}_{ijt}^{Fuel}$$

$$(\mathrm{CarbonCaptureCost})_t^{\mathrm{New,Fuel}} = \sum_i \sum_j Q_{ijt}^{New,Fuel} \varepsilon_{ijt}^{New,Fuel} \hat{B}_{ijt}^{New,Fuel}$$

The total energy produced from the fuel is calculated using a conversion factor that converts the barrel of raw material that is processed into the amount of stored energy of the product that it produces. This is done so the model can compare the various different type of transport fuel.

$$E_{it}^{Fuel} = \sum_j k_{it}^{Fuel} \hat{B}_{ijt}^{Fuel}$$

$$E_{it}^{New,Fuel} = \sum_j k_{it}^{Fuel} \hat{B}_{ijt}^{New,Fuel}$$

To find the fixed capital investment for new plants and refineries, a linear approximation was made. The number of plants that can be built is limited and the new capacity is limited between a maximum and minimum:

$$\sum_t^n \hat{y}_{ijt}^{New,Elect} \leq 1$$

$$\sum_t^n \hat{y}_{ijt}^{New,Fuel} \leq 1$$

$$\left(C_{ijt}^{New,Elect}\right)_{Min} \hat{y}_{ijt}^{New,Elect} \leq \hat{C}_{ijt}^{New,Elect} \leq \left(C_{ijt}^{New,Elect}\right)_{Max} \hat{y}_{ijt}^{New,Elect}$$

$$\left(C_{ijt}^{New,Fuel}\right)_{Min} \hat{y}_{ijt}^{New,Fuel} \leq \hat{C}_{ijt}^{New,Fuel} \leq \left(C_{ijt}^{New,Fuel}\right)_{Max} \hat{y}_{ijt}^{New,Fuel}$$

Natural Gas Heating Model

Below is a breakdown of the total natural gas heating operational cost model. The symbols that are used are similar to the electric and fuel model:

$$(\mathrm{TotalCost})_t^{\mathrm{Heat}} = (\mathrm{FixedOprCost})_t^{\mathrm{Heat}} + (\mathrm{VarOprCost})_t^{\mathrm{Heat}}$$

Below is a breakdown of the various costs:

$$(\text{FixedOprCost})_{\text{t}}^{\text{Heat}} = \sum_i \sum_j F_{ijt}^{\text{Heat}}$$

$$(\text{VarOprCost})_{\text{t}}^{\text{Heat}} = \sum_i \sum_j V_{ijt}^{\text{Heat}} \hat{E}_{ijt}^{Heat}$$

Profitability Model

Maximizing the annual profit is the main objective of the model. For the equations below, only the electric equations are shown. The other industries use the same equations. In order to make the equation linear the electricity price and the tax break alpha is treated as a parameter. Alpha is the percent of gross profit that is given back as tax breaks. Various scenarios using different price and alpha was ran to find the optimal values. The electricity price is regulated, but the price of fuel and natural gas is determined by the market and cannot be manipulated.

$$(\text{AnnualProfit})_{\text{t}}^{\text{Elect}} = \sum_i \sum_j (\text{GrossProfit})_{\text{ijt}}^{\text{Elect}} - \sum_i \sum_j (\text{Taxes})_{\text{ijt}}^{\text{Elect}}$$

$$(\text{GrossProfit})_{\text{ijt}}^{\text{Elect}} = (\text{Revenue})_{\text{ijt}}^{\text{Elect}} - (\text{OperationCost})_{\text{t}}^{\text{Elect}}$$

$$(\text{Revenue})_{\text{ijt}}^{\text{Elect}} = (\text{EnergyGenerated})_{\text{ijt}}^{\text{Elect}} (\text{Price})_{\text{t}}^{\text{Elect}}$$

$$(\text{OperationCost})_{\text{ijt}}^{\text{Elect}} = (\text{FixedOprCost})_{\text{ijt}}^{\text{Elect}} + (\text{VarOprCost})_{\text{ijt}}^{\text{Elect}} + (\text{FuelCost})_{\text{ijt}}^{\text{Elect}} + (\text{CarbonCaptureCost})_{\text{ijt}}^{\text{Elect}}$$

$$(\text{Taxes})_{\text{ijt}}^{\text{Elect}} = (\text{TaxRate})(\text{GrossProfit})_{\text{ijt}}^{\text{Elect}}$$

For the new plants and refineries the profitability equation are the same except that there is a depreciation cost and tax breaks.

$$(\text{AnnualProfit})_{\text{t}}^{\text{New,Elect}} = \sum_i \sum_j (\text{GrossProfit})_{ijt}^{New,Elect} - \sum_i \sum_j (\text{Taxes})_{ijt}^{New,Elect} + \sum_i \sum_j (\text{TaxBreaks})_{ijt}^{New,Elect}$$

$$(\text{GrossProfit})_{\text{ijt}}^{\text{New,Elect}} = (\text{Revenue})_{\text{ijt}}^{\text{New,Elect}} - (\text{Depreciation})_{\text{ijt}}^{\text{New,Elect}} - (\text{OperationCost})_{\text{ijt}}^{\text{New,Elect}}$$

$$(\text{Revenue})_{\text{ijt}}^{\text{New,Elect}} = (\text{EnergyGenerated})_{\text{ijt}}^{\text{New,Elect}} (\text{Price})_{\text{t}}^{\text{Elect}}$$

$$(\text{Depreciation})_{\text{ijt}}^{\text{New,Elect}} = \frac{FCI_{\text{ijt}}^{\text{New,Elect}}}{m}$$

$$(\text{OperationCost})_{\text{ijt}}^{\text{New,Elect}} = (\text{FixedOprCost})_{\text{ijt}}^{\text{New,Elect}} + (\text{VarOprCost})_{\text{ijt}}^{\text{New,Elect}} + (\text{FuelCost})_{\text{ijt}}^{\text{New,Elect}} + (\text{CarbonCaptureCost})_{\text{ijt}}^{\text{New,Elect}}$$

$$(\text{Taxes})_{\text{ijt}}^{\text{New,Elect}} = (\text{TaxRate})(\text{GrossProfit})_{\text{ijt}}^{\text{New,Elect}}$$

$$(\text{TaxBreaks})_{\text{ijt}}^{\text{New,Elect}} = \alpha_{\text{ijt}}^{\text{New,Elect}} (\text{GrossProfit})_{\text{ijt}}^{\text{New,Elect}}$$

Constraints

Energy Demand Constraints

The summation of all the energy from all fuel that is produced must be greater than demand.

$$\sum_{Electric}\left(EnergyGeneratedTotal\right)_t^{Electric} = \left(EnergyDemand\right)_t^{Electric}$$

$$\sum_{Fuel}\left(EnergyGeneratedTotal\right)_t^{Fuel} = \left(EnergyDemand\right)_t^{Fuel}$$

$$\sum_{Heat}\left(EnergyGeneratedTotal\right)_t^{Heat} = \left(EnergyDemand\right)_t^{Heat}$$

CO₂ emission constraints

The Total Net CO_2 emitted from both electric and fuel industry must be less than the limit that is set.

$$\sum_{Elect}\left(NetCO2Emission\right)_t^{Elect} + \sum_{Fuel}\left(NetCO2Emission\right)_t^{Fuel} + \sum_{Heat}\left(NetCO2Emission\right)_t^{Heat} \leq \left(CO2Limit\right)_t$$

The Net CO2 emitted is equal to the CO2 generated from the refineries minus the CO2 that is removed using Carbon Capture Sequestration.

$$\left(\mathrm{NetCO2Emission}\right)_{\mathrm{t}}^{\mathrm{Electric}} = \left(\mathrm{CO2Produced}\right)_{\mathrm{t}}^{\mathrm{Electric}} - \left(\mathrm{CO2Removed}\right)_{\mathrm{t}}^{\mathrm{Electric}}$$

$$\left(\mathrm{NetCO2Emission}\right)_{\mathrm{t}}^{\mathrm{Fuel}} = \left(\mathrm{CO2Produced}\right)_{\mathrm{t}}^{\mathrm{Fuel}} - \left(\mathrm{CO2Removed}\right)_{\mathrm{t}}^{\mathrm{Fuel}}$$

$$\left(\mathrm{CO2Produced}\right)_{\mathrm{t}}^{\mathrm{Electric}} = \gamma_{ijt}^{Elect}\hat{E}_{ijt}^{Elect}P_t^{Elect} + \gamma_{ijt}^{New,Elect}\hat{E}_{ijt}^{New,Elect}P_t^{Elect}$$

$$\left(\mathrm{CO2Produced}\right)_{\mathrm{t}}^{\mathrm{Fuel}} = \gamma_{ijt}^{Fuel}\hat{E}_{ijt}^{Elect}P_t^{Fuel} + \gamma_{ijt}^{New,Fuel}\hat{E}_{ijt}^{New,Elect}P_t^{Fuel}$$

$$\left(\mathrm{CO2Removed}\right)_{\mathrm{t}}^{\mathrm{Elect}} \leq \varepsilon_{ijt}^{Elect}\left(\mathrm{CO2Produced}\right)_{\mathrm{t}}^{\mathrm{Elect}} + \varepsilon_{ijt}^{New,Elect}\left(\mathrm{CO2Produced}\right)_{\mathrm{t}}^{\mathrm{Elect}}$$

$$\left(\mathrm{CO2Removed}\right)_{\mathrm{t}}^{\mathrm{Fuel}} \leq \varepsilon_{ijt}^{Fuel}\left(\mathrm{CO2Produced}\right)_{\mathrm{t}}^{\mathrm{Fuel}} + \varepsilon_{ijt}^{New,Fuel}\left(\mathrm{CO2Produced}\right)_{\mathrm{t}}^{\mathrm{Fuel}}$$

Capacity Constraints

The amount of processed Raw Material must be less than existing and new capacity at all refineries. The amount of switch grass and soybean available to buy must be less than the annual production available.

$$\hat{E}_{ijt}^{Electric} \leq \hat{C}_{ij}^{Electric}$$

$$\hat{B}_{ijt}^{Fuel} \leq \hat{C}_{ijt}^{Fuel}$$

$$\hat{E}_{ijt}^{Heat} \leq \hat{C}_{ijt}^{Heat}$$

$$\hat{B}_{Switchgrass} \leq \left(Annual\ Limit\right)_{Switchgrass}$$
$$\hat{B}_{Soybean} \leq \left(Annual\ Limit\right)_{Soybean}$$

Job Creation

New job from new plants and refineries as represented by salary must increase by a preset limit. New salary is divided into construction and operational.

$$\sum_{i}\left(NewSalary\right)_{t}^{Electric} + \sum_{i}\left(NewSalary\right)_{t}^{Fuel} \geq \left(NewSalaryLimit\right)_{t}^{Electric}$$

$$\sum_{i}\left(NewSalary\right)_{t}^{Electric} = \sum_{i}\left(Construction\right)_{t}^{Electric} + \sum_{i}\left(Operation\right)_{t}^{Electric}$$

$$\sum_{i}\left(NewSalary\right)_{t}^{Fuel} = \sum_{i}\left(Construction\right)_{t}^{Fuel} + \sum_{i}\left(Operation\right)_{t}^{Fuel}$$

Profitability

The annual profit from new plants and/or refineries must meet a preset ROI.

$$(\mathrm{AnnualProfit})_{\mathrm{t}}^{\mathrm{New,Elect}} \geq (ROI)_{\mathrm{ij}}^{\mathrm{New,Elect}} \sum_{t}^{\mathrm{t}} \sum_{i} \sum_{j} (FCI)_{\mathrm{ijt}}^{\mathrm{New,Elect}}$$

$$(\mathrm{AnnualProfit})_{\mathrm{t}}^{\mathrm{New,Fuel}} \geq (ROI)_{\mathrm{ij}}^{\mathrm{New,Elect}} \sum_{t}^{\mathrm{t}} \sum_{i} \sum_{j} (FCI)_{\mathrm{ijt}}^{\mathrm{New,Elect}}$$

Results

In this section, the results of our model are presented. Various scenarios of percent yearly CO_2 reductions and job salary increases were ran to create a pareto-optimal boundary surface. Scenarios at different electricity prices run in order to find out how much electricity prices will need to be increased by to achieve specified return of investments.

Net Present Value: Pareto-optimal Boundary

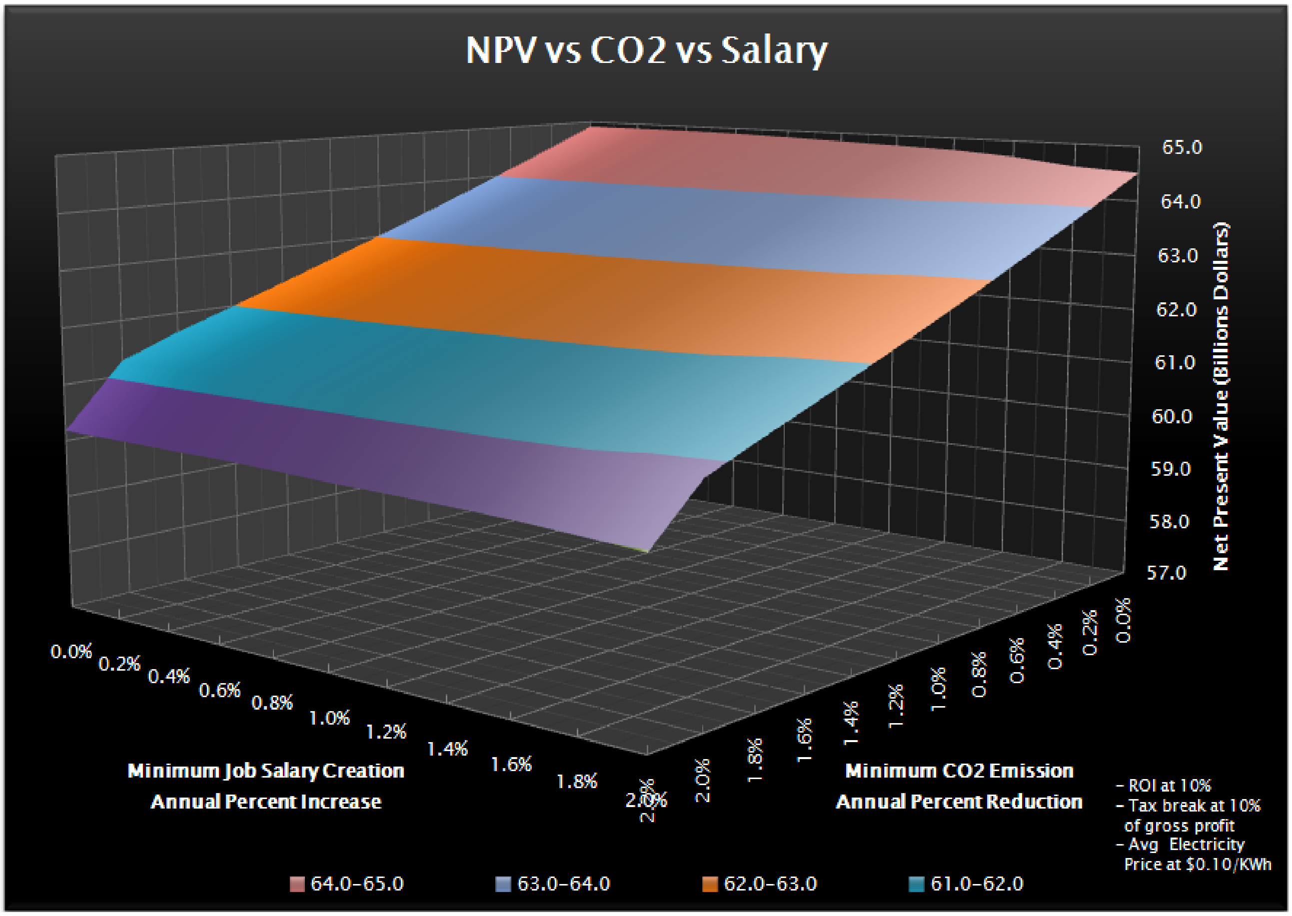


Figure 21. Pareto-optimal Boundary: NPV vs. CO2 vs. Salary

The figure above is the pareto-optimal boundary surface for the net present value of Oklahoma's entire energy industry from 2010 to 2030. It represents the maximum profit that the energy industry can make at a specific annual minimum CO_2 percent reduction rate and minimum job salary increase. The maximum possible rate for CO_2 reduction was found to be 2.2% and the maximum job salary increase was found to be 2%. Net present value is strongly affected by the CO_2 reduction rate due to the high costs of using carbon capture and sequestration and building cleaner electricity producing facilities such as wind farms and hydroelectric plants. The sharp NPV decrease after 2% CO_2 reduction rate is caused by using more carbon capture and sequestration. This is the primary reason for the steeper slope. We found that job salary creation had only a minor effect on NPV. Further explanation will be presented with the graphs below.

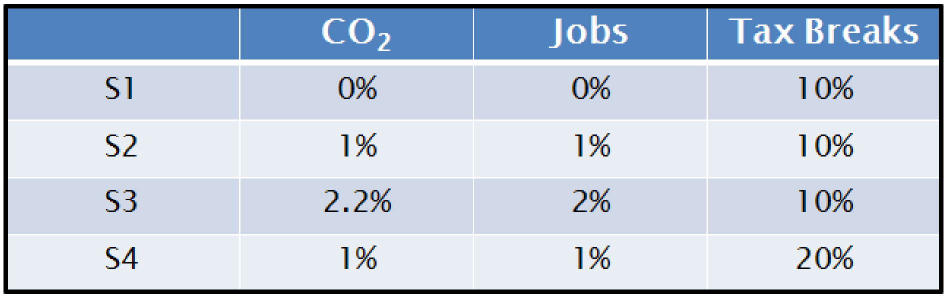
Minimum Retail Electricity Prices

		Tax Breaks (percent of profit)			
CO_2	ROI	0%	10%	20%	30%
0.0%	2.5%	N/A	$ 0.05	$ 0.05	$ 0.05
0.0%	5.0%	N/A	$ 0.07	$ 0.07	$ 0.06
0.0%	7.5%	N/A	$ 0.09	$ 0.08	$ 0.08
0.0%	10.0%	N/A	$ 0.10	$ 0.09	$ 0.09
1.0%	2.5%	N/A	$ 0.06	$ 0.06	$ 0.06
1.0%	5.0%	N/A	$ 0.07	$ 0.07	$ 0.06
1.0%	7.5%	N/A	$ 0.09	$ 0.08	$ 0.08
1.0%	10.0%	N/A	$ 0.10	$ 0.10	$ 0.09
2.0%	2.5%	N/A	$ 0.07	$ 0.07	$ 0.07
2.0%	5.0%	N/A	$ 0.07	$ 0.07	$ 0.07
2.0%	7.5%	N/A	$ 0.09	$ 0.08	$ 0.08
2.0%	10.0%	N/A	$ 0.10	$ 0.10	$ 0.09

Figure 22. (Table 12) Minimum retail electricity price ($/kWh) required at various scenario (Jobs at 1%)

Figure 22 shows the minimum average electricity price required over the next 20 years for new investors to make a given return on investment at different CO_2 reduction levels, and tax breaks given. For all scenarios job salary increase was kept constant at 1%. The table shows that if no tax breaks are given, it will not be profitable to invest in new power plants for any given scenario. Furthermore, at 10% ROI it shows that the retail price of electricity will need to be increase to at least $0.09 per kWh from the current price of $0.072 per kWh. As expected, increasing the CO_2 reduction will result in higher electricity prices.

Scenarios

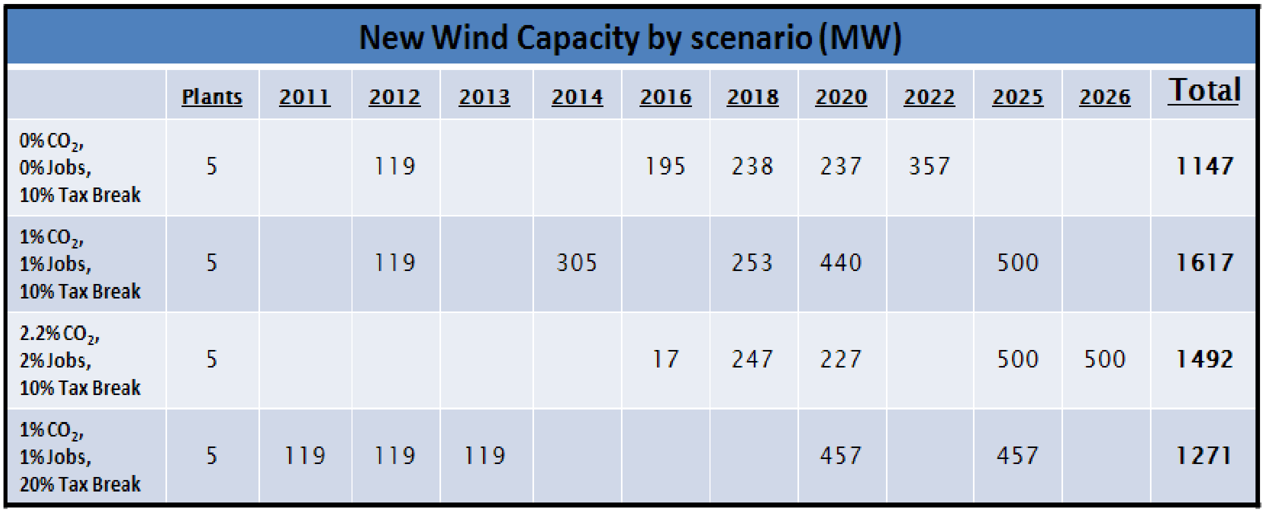


	CO_2	Jobs	Tax Breaks
S1	0%	0%	10%
S2	1%	1%	10%
S3	2.2%	2%	10%
S4	1%	1%	20%

Figure 23. (Table 13) Scenarios chosen for analysis

For the rest of this report, four scenarios will be presented. Three scenarios were chosen and explored in more detail in order to determine the effects of increasing CO_2 reduction and job salary increase from the minimum to the maximum possible. A fourth scenario, with higher tax breaks, was also chosen. For all four scenarios the retail price of electricity is kept constant at 10 cent per kWh and the ROI is kept constant at 10%. We believe an average of 10 cent per kWh is a reasonable assumption to make for the next 20 years. A 10% ROI is chosen because it is likely the minimum amount required for most investors to put in money.

New Plants and Refineries



New Wind Capacity by scenario (MW)												
	Plants	2011	2012	2013	2014	2016	2018	2020	2022	2025	2026	Total
0% CO_2, 0% Jobs, 10% Tax Break	5		119			195	238	237	357			**1147**
1% CO_2, 1% Jobs, 10% Tax Break	5		119		305		253	440		500		**1617**
2.2% CO_2, 2% Jobs, 10% Tax Break	5					17	247	227		500	500	**1492**
1% CO_2, 1% Jobs, 20% Tax Break	5	119	119	119				457		457		**1271**

Figure 24. (Table 14) New wind farm construction

New hydro-plant capacity by scenario (MW)

	Plants	2010	2013	2014	2017	2020	2024	2025	2026	Total
0% CO_2, 0% Jobs, 10% Tax Break	3	121	400					357		**678**
1% CO_2, 1% Jobs, 10% Tax Break	4	121	400					50	345	**916**
2.2% CO_2, 2% Jobs, 10% Tax Break	5			119	181	400		384	400	**1484**
1% CO_2, 1% Jobs, 20% Tax Break	5	180		357	376		119		50	**1083**

Figure 25. (Table 15) New hydroelectric plant construction

Figures 24 and 25 are the model's wind farm and hydroelectric plant construction results. Oklahoma's government needs to promote the construction of plants and refineries that use clean sustainable energy sources in order to reduce the carbon footprint of the state. Reflecting this, we gave our model the option to choose whether to build a maximum of five wind farms, five hydroelectric plants, two biodiesel, and two ethanol refineries as well as select the capacity and construction year for each. We found that for different scenarios, the model arrives at different values for new plant capacities as well as their optimal construction year. At low CO_2 reduction and job salary increase, wind plants are favored. At high CO_2 reduction and job salary increase, either plant is favored equally. At high CO_2 reduction levels, plants should be built at a later time. The model chose to compensate this by using more carbon capture and sequestration at an earlier time. This will be explained in more detail later on. The model determined that no new biodiesel or ethanol refineries should be built. This is because the demand for transportation fuel is not forecasted to increase enough for them to be profitable.

	0% CO_2, 0% Jobs, 10% Tax Break	1% CO_2, 1% Jobs, 10% Tax Break	2.2% CO_2, 2% Jobs, 10% Tax Break	1% CO_2, 1% Jobs, 20% Tax Break
# of Wind Plant	5 farms	5 farms	5 farms	5 farms
Total Capacity	1147 MW	1617 MW	1492 MW	1271 MW
# of Hydroelectric	3 plants	4 plants	5 plants	5 plants
Total Capacity	678 MW	916 MW	1484 MW	1083 MW
Avg ROI	9.6%	10.1%	10.1%	10.2%
Std Deviation	2.0%	2.4%	2.7%	2.3%

Figure 26. (Table 16) Wind and hydroelectric summary and ROI

Figure 26 is a summary of the power plant constructions. For all scenarios, a 10% annual ROI is possible with a standard deviation ranging from 2%-2.7%.

New Salaries

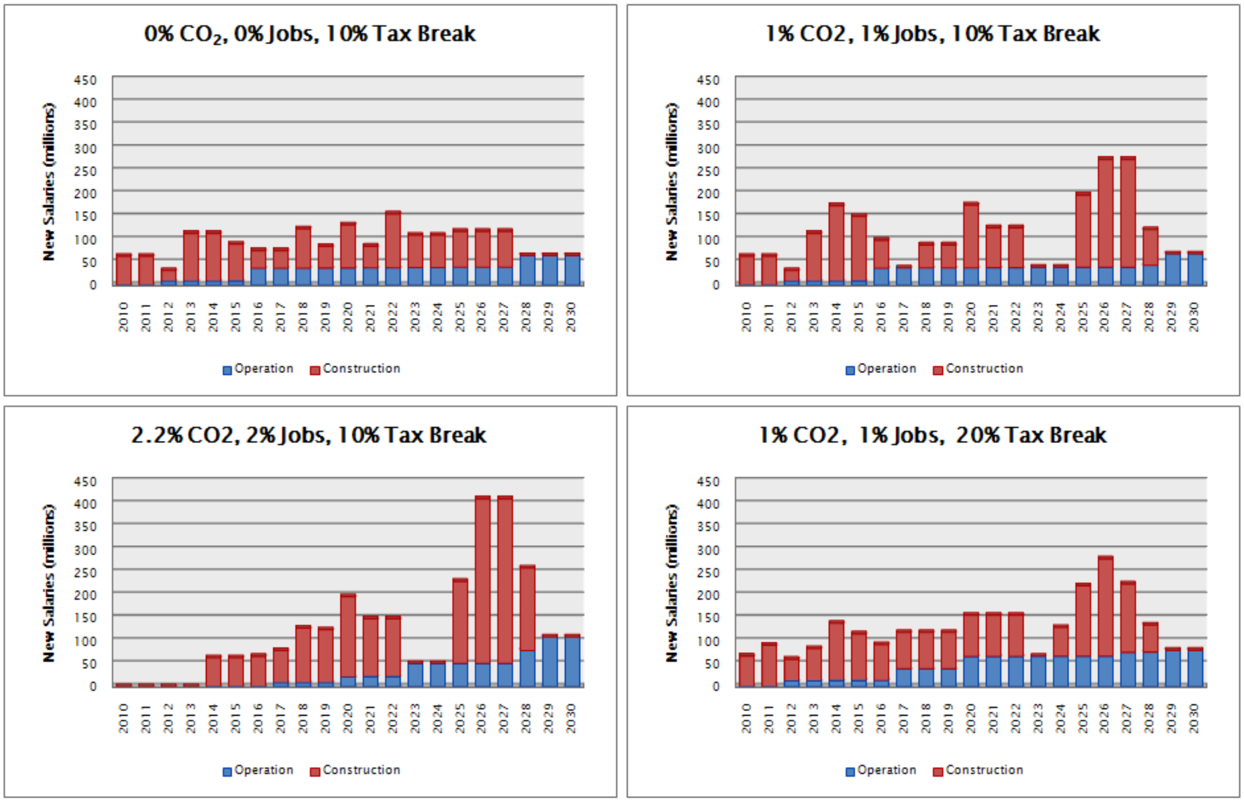


Figure 27. New construction and operation salaries

Figure2 7 represents job creation in the form of total salaries paid to Oklahoma workers through construction and plant operation jobs. Because only hydroelectric plants and wind farms are being constructed, little plant operation salaries are being paid. As mentioned previously, figure 27 shows that at high CO_2 reduction levels plants should be built at a later time. The total salary coming from plant operation is shown to be significantly lower than construction labor. This is because only wind and hydroelectric plants are built. Both facilities require less people to operate them when compared to coal and natural gas plants. Wind farms require virtually no maintenance and hydroelectric plants are mostly automated. Figure 27 also shows that higher tax breaks have only a small effect on salary.

Profits

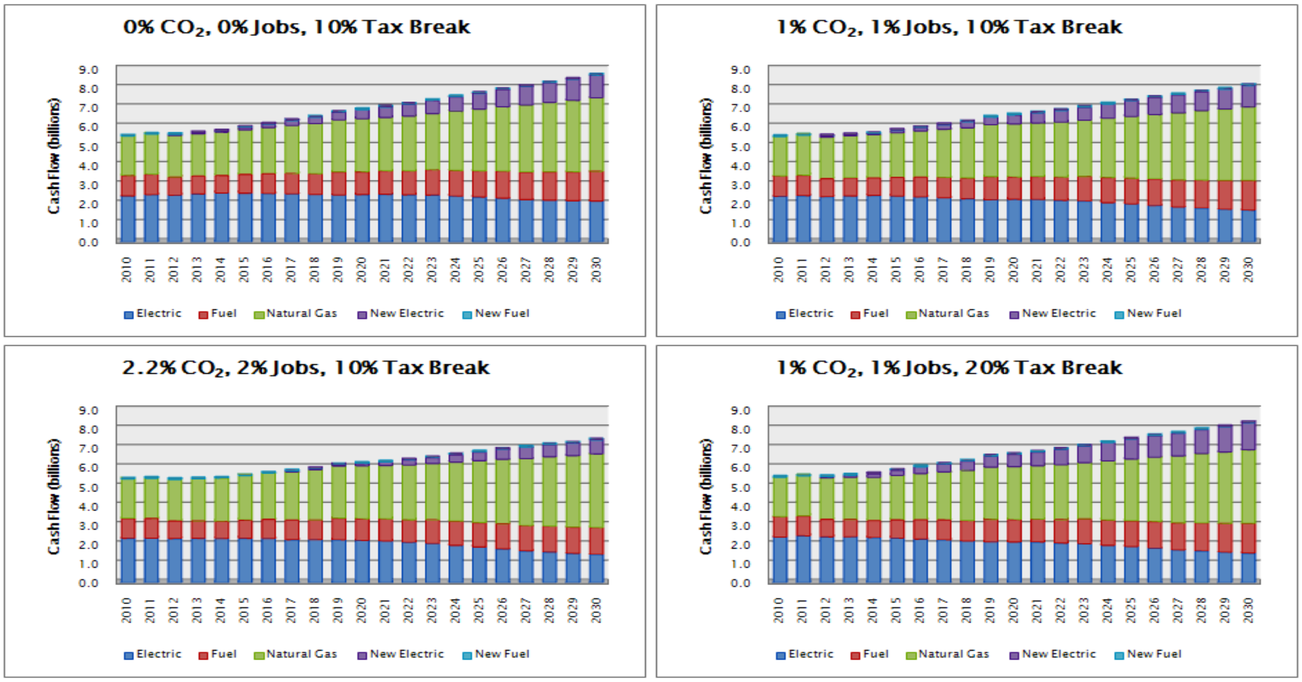


Figure 28. Annual Cash Flow from all industries

Figure 28 is the annual cash flow from all industries in 2009 dollars. It shows that at higher CO_2 reduction levels, the electric industry loses profit. More specifically, profit loss is primarily from coal plants and is due to the cost of using more carbon capture and sequestration.

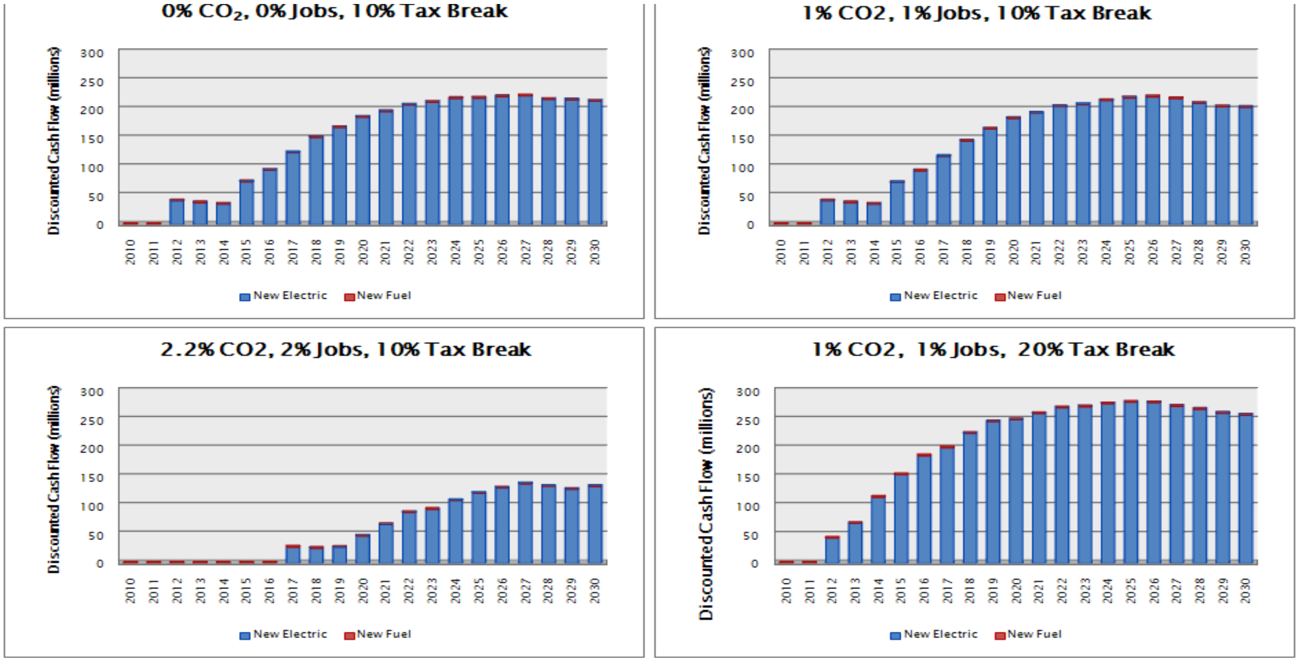
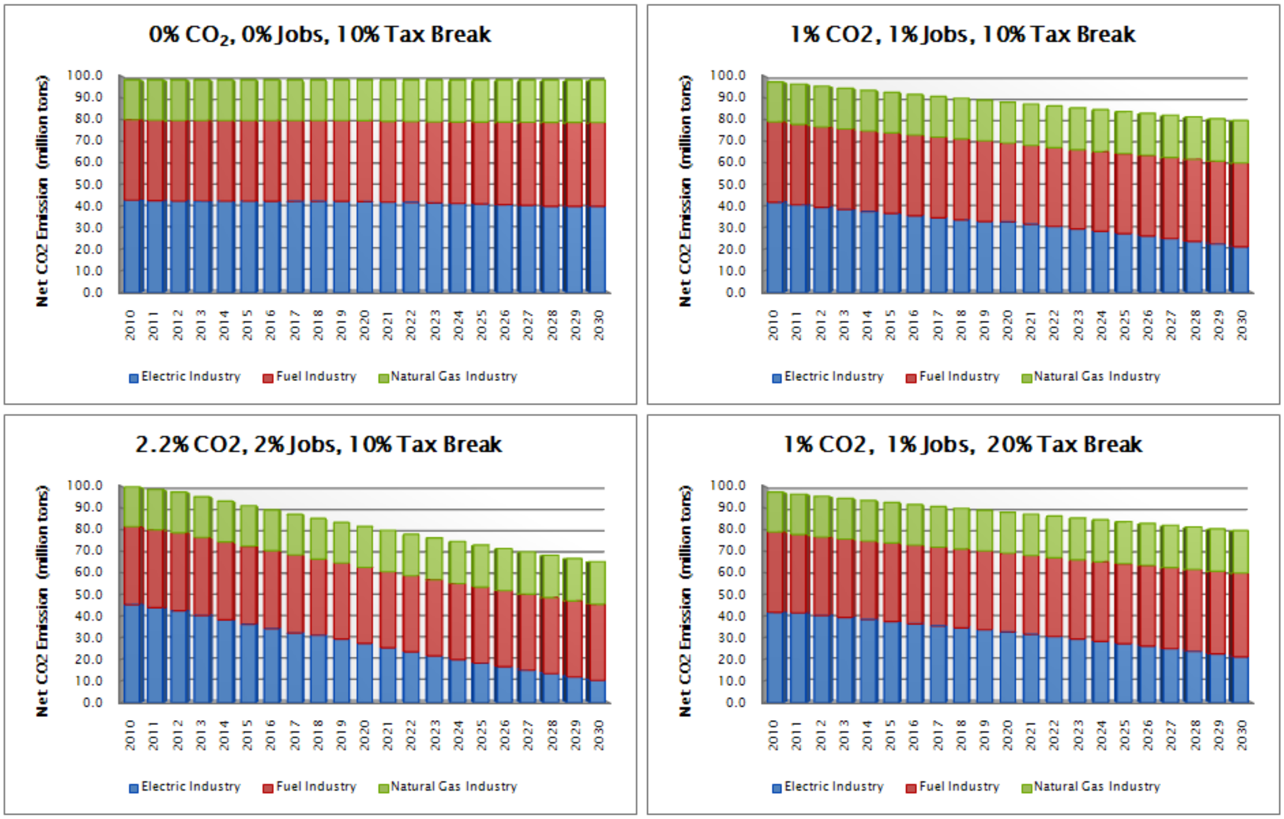


Figure 29. Discounted Cash Flow at 8% for new plants and refineries

Figure 29 represents the discounted annual cash flow at an 8% discount rate for new electric plants and refineries. Since there are no refineries that are built, the graph shows only the cash flow from electric power plants. Profit is shown to decrease as CO_2 reduction levels and job salaries increase. However, results are similar for all scenarios under a 2% CO_2 reduction. After 2% reduction, profit is shown to be significantly reduced. At values larger than 2% reduction, the model chooses to build most plants during the second half of the project's life. This is compensated by using more carbon capture and sequestration towards the beginning. As expected, a higher tax break gives investors significantly higher profits.

Net CO2 Emissions after CCS



0% CO_2, 0% Jobs, 10% Tax Break

1% CO2, 1% Jobs, 10% Tax Break

2.2% CO2, 2% Jobs, 10% Tax Break

1% CO2, 1% Jobs, 20% Tax Break

Figure 30. Net CO2 Emission after CCS

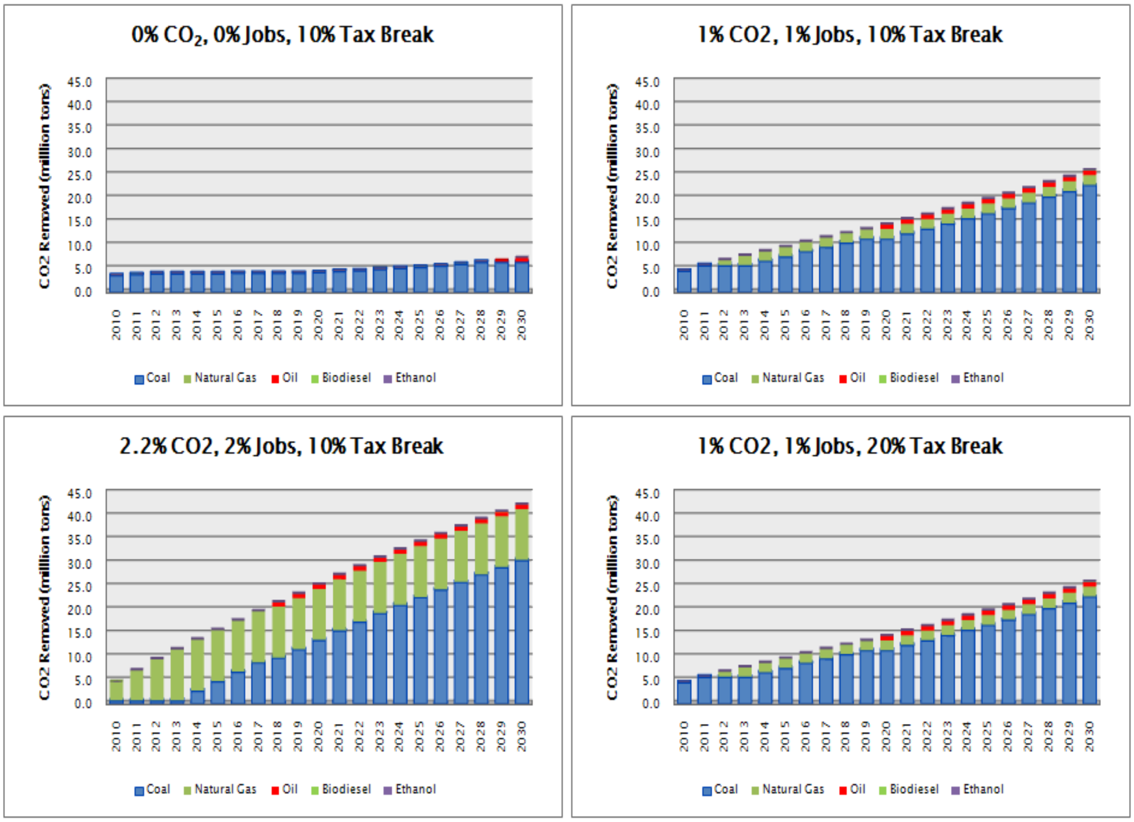


Figure 31. CO2 Emissions Captured with CCS

Figure 30 represents the net CO_2 emission after using CCS from all industries. Figure 31 shows the amount that is captured by CCS. Figure 30 includes the CO_2 emission amounts from plants, refineries, and consumers. The majority of CO_2 emissions in industry are from power plants, specifically from coal power plants. Carbon capture and sequestration use increases with the CO_2 reduction level. We found that most carbon capture and sequestration is done by the electric industry, specifically coal plants. The reason for this is that CCS is cheaper for coal plants due to more readily available technology. After 2% reduction, the model show that more CCS usage from natural gas plants should be done and at an earlier time than coal plants. There is minor CCS from oil refineries. This is because refineries produce little CO_2 emissions compared to coal and natural gas plants. Most of the CO_2 being emitted from transportation fuel is from consumer consumption and cannot be captured with CCS.

Electricity Generation and Transportation Fuel Production

Figures 32 and 33 represent the distribution of electricity generation by source and the distribution of transportation fuel over the next 20 years, respectively. There is little change in the generation from coal and natural gas plants for all scenarios. Generation from wind farms and hydroelectric plants is shown to steadily increase. Wind and hydroelectric are shown to increase to 24% and 15% of the total generation by 2030, respectively. The transportation fuel industry is shown to remain virtually unchanged as most all of the demand is met by gasoline and diesel. As previously mentioned, the demand is not expected to increase enough for biodiesel and ethanol to be profitable.

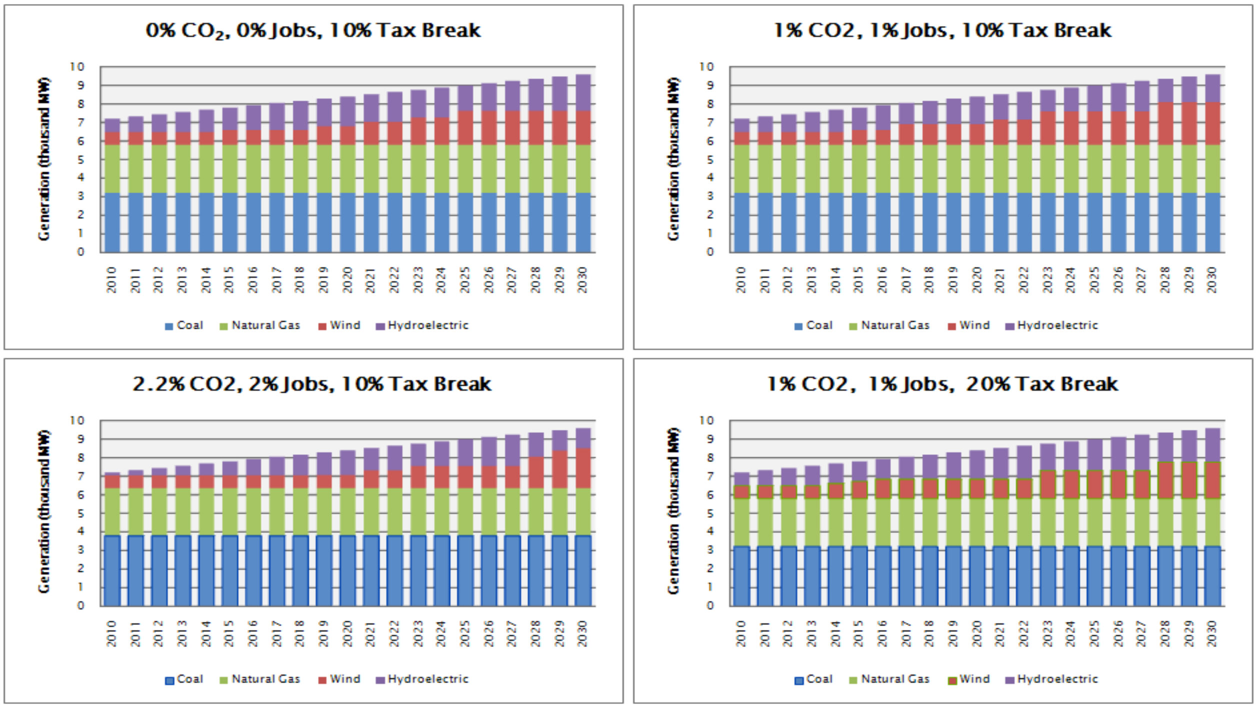


Figure 32. Electricity Generation

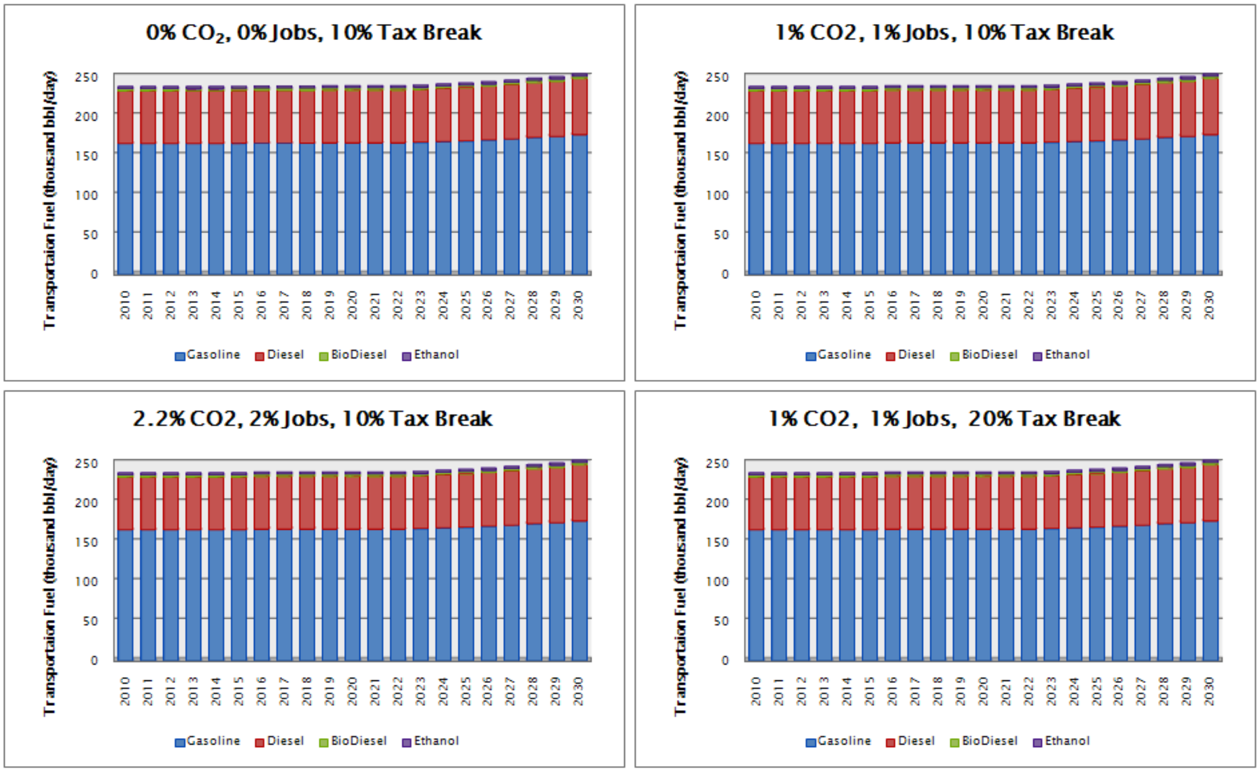


Figure 33. Transportation Fuel Production

Conclusions

The goal of our mathematical model is to give guidance on how to proceed in changing Oklahoma's energy infrastructure. This change comes in the form of reducing yearly CO_2 emissions and increasing job salaries paid to Oklahoma workers while still meeting projected energy demands for the next twenty years. After developing our model, we ran hundreds of trials and analyzed the results of each one. After this detailed analysis we conclude that of all the industries studied, only the electric industry is in need of drastic change. Electricity generation from the combustion of coal produces the most CO_2 of any energy type and makes up more than half of Oklahoma's electric capacity. To combat this overwhelming coal use, the model chooses to have coal plants use carbon capture and sequestration technology to reduce CO_2 emissions. At the same time, the model chooses to build more wind farms and hydroelectric plants in order to meet the state's increased future electricity demand. We found that government tax breaks are needed in order to make our energy industry profitable enough to attractive investors. We also found that electricity prices will need to be increased to at least $0.10/kilowatt-hour to ensure potential investors receive the minimum acceptable return on their investments. We have determined that little change is warranted for the transportation fuel industry. This is because the fuel industry produces far less CO_2 than the electric industry, as the majority of transportation fuel CO_2 emissions come from end-use consumption. We found that change in the transportation fuel industry should be made on the consumer level. The production of biodiesel and ethanol is not profitable because there is not enough demand for it. Government involvement in the form of tax breaks and incentives should be increased in order to persuade consumers to use more bio-fuels. In conclusion, our model is a great first step in planning Oklahoma's energy industry provides good approximations. Upon further research into Oklahoma's energy infrastructure and improvement on the model, this project has the potential to produce very good results.

Further Studies

Due to time constraints, many things were simplified or not included in the formulation of our mathematical models. The broad scope of our project did not allow for some areas to be studied in fine detail, while others were omitted entirely. Examples of this include; detailed calculation of operating and maintenance costs for varying energy facilities, electricity generation from solar and photo-voltaic cells, possible need for natural gas distribution pipeline expansions, government involvement in consumer bio-fuel use, and the advantages of improving the efficiency of the electric distribution grid.

Operating and Maintenance Costs

Further research should be done in calculating both the fixed and variable operating and maintenance costs of Oklahoma energy creation facilities. Our data for these costs were taken from reliable sources and can be considered fairly accurate. Information we found for O&M costs were typically given in dollars per capacity (i.e. $/Mwh) and varied for each of the eight energy types studied. However, this data assumes that all plants within a certain plant type have the same associated costs. Through related research we found that this is not necessarily true. For this reason, using the average costs for any given plant type cannot be deemed adequately accurate for use in our detailed models. Further research should work to identify Oklahoma plant costs on an individual basis.

Solar/ PV cells

During the first stages of project research it was deemed that solar technology would not be included in our project. Oklahoma does not have the adequate conditions for large scale electricity generation via solar energy. Electricity generation from solar or PV sources in Oklahoma is limited to small scale residential and industrial use. Incorporation of this energy use would require massive amounts of research and modeling while only contributing minor results. Further research into planning Oklahoma's energy industry should incorporate solar and PV electricity generation. Specifically, how government tax breaks and incentives can affect the number of homes and businesses generating their own electricity with PV cells instead of purchasing electricity from utility companies. This increased PV cell use could potentially lower the demand for utility sold electricity in the state and greatly affect the model's results.

Natural Gas

Forecasted Demand

Much of the energy generation and consumption data required for our project required enormous search efforts to locate and deem reliable. Some of the data could not be found at all. The forecasted natural gas demand of the state was one of these. Forecasted natural gas demand for the entire U.S. was readily available though. In order to approximate the forecasted natural gas heating for Oklahoma's next 20 years, a percent yearly change in forecasted U.S. use was found for each of the four heating sectors. This yearly percent increase or decrease was then applied to Oklahoma's current natural gas use. This method allowed for the rough approximation of Oklahoma's natural gas use over the next 20 years, assuming it follows the same trends as U.S. use. Further research into this project should work to find more accurate forecasts for natural gas heating use.

Pipeline Expansion

To further simplify our models, the potential need for an expansion of the state's natural gas distribution pipeline was not researched. The current models assume that no new pipelines will need to be built for the next twenty years. This may not be the case however. Residential natural gas use in the U.S. is forecasted to increase 3% over the next 20 years while total natural gas use for heating is forecasted to increase by over 6%. This increased use could possible see the need for expansions within the state's natural gas distribution system. Costly expansions could cause increased prices and therefore a subsequent decrease in natural gas use as more consumers turn to electric or PV cell heating to heat their homes. This potential course of events could alter the results of the model. These changes could range anywhere from insignificant to considerable, only further investigation on the subject will tell.

Consumer Bio-Fuel Use

The majority of CO_2 emissions associated with the transportation fuel industry come from end-use combustion in vehicles. Because this fuel use and subsequent CO_2 emission cannot be regulated in the scope of our project, these emissions were not included. However, emissions from consumer vehicles can be modeled and the effect of their changes can be studied. Government incentives to use low emission vehicles and bio-fuels could drastically change both emissions and bio-fuel demand data. Further research into consumer bio-fuel use and government involvement should be done.

Electric Grid Improvement

Although the following topic does not directly relate to the type of research and modeling done in this project, it is still worth mentioning. It was estimated that over 7% of the United States' electricity was lost during grid transmission in 1995. Oklahoma produced over 3.7 million megawatt-hours of electric energy in 2008. Assuming that Oklahoma loses 7% of electricity during transmission, improving the electric distribution grid to 6% losses could save over 37,000 megawatt-hours of energy[3]. This increased efficiency could drastically lower consumer electricity prices and CO_2 emissions to the environment. To illustrate, in producing 37,000 megawatt-hours of energy, a coal plant produces over 85 million pounds of CO_2[3]. Research in this area would focus on the CO_2 emissions reduced by grid improvement and what the state government can do to encourage this technological change rather than on how the change itself can be accomplished.

References

1. www.owrb.ok.gov/util/waterfact.php
2. www.farmland.org/resources
3. eia.gov
4. www.seic.okstate.edu/owpi/#none
5. www.eia.doe.gov/pub/oil_gas/petroleum/data_publications/refinery_capacity_data/historical/2008/table3.pdf
6. www.ethanolproducer.com/plant-list
7. www.biodieselmagazine.com/plant-list.
8. www.okcommerce.gov
9. www.seic.okstate.edu/owpi
10. www.bts.gov/publications/state_transportation_statistics/oklahoma/
11. www.awea.org/projects/Projects.aspx?s=Oklahoma
12. Combustion of fat and vegetable oil derived fuels in diesel engines
    Michael graboski and Robert mccormick
13. www.nrel.gov/docs/fy05osti/37136.pdf
14. Radich, Anthony; Biodiesel performance, costs, and use
15. numero57.net/?p=255
16. www.eia.doe.gov/kids/energyfacts/sources/non-renewable/oil.html
17. www.highplainsbioenergy.com
18. www.earthbiofuels.com
19. www.ag.ndsu.edu/pubs/ageng/machine/ae1240.pdf
20. www.biodieselnow.com/forums/t/9557.aspx
21. tonto.eia.doe.gov/oog/info/gdu/gasdiesel.asp
22. www.afdc.energy.gov/afdc/pdfs/afpr_oct_08.pdf
23. www.biodiesel.org/pdf_files/fuelfactsheets/BTU_Content_Final_Oct2005.pdf
24. www.cyberlipid.org/glycer/biodiesel.htm
25. journeytoforever.org/biodiesel_yield.html
26. “Biodiesel: The Sustainability Dimensions.” ATTRA Publication. Butte, MT: National Center for Appropriate Technology. Pages 4-5
27. www.usda.gov/oce/reports/energy/USDA_2002_ETHANOL.pdf
28. www.ethanolrfa.org/industry/statistics/
29. www.e85prices.com/
30. www.learnaboutcellulosicethanol.org/environment.html
31. ethanol-gasolinesources.com/
32. www.ethanolrfa.org/industry/statistics/
33. jbkart.blogspot.com/2007_09_01_archive.html
34. www.windustry.org
35. www.seic.okstate.edu/owpi/OKWindInfo/OWPI_documents/Oklahoma_Wind_Farms.pdf
36. www.autobloggreen.com/2008/04/25/oklahoma-bioenergy-center-gets-1-100-acres-to-plant-switchgrass/
37. jdsutter.com/portfolio/switchgrass.pdf

38. bioenergy.ornl.gov/reports/graham/southernplains.html
39. news.mongabay.com/2008/0107-switchgrass.html
40. www.afdc.energy.gov/afdc/sabre/sabre.php
41. bioenergy.ornl.gov/papers/misc/energy_conv.html
42. www.epa.gov/otaq/climate/420f05001.htm
43. www.nrel.gov/vehiclesandfuels/npbf/pdfs/24772.pdf
44. www.transportation.anl.gov/pdfs/TA/271.pdf
45. tonto.eia.doe.gov/state/state_energy_profiles.cfm?sid=OK
46. uwspace.uwaterloo.ca/bitstream/10012/3418/1/Hamids%20Thesis%20Revision%2014-PDF%20version.pdf
47. www.awea.org/resources/financing/documents/AWEAAnalysis8-9-046P1.pdf
48. www.ethree.com/GHG/20%20Hydro%20Assumptions%20v4.doc
49. me.queensu.ca/courses/MECH430/Assets/Files/Recommended%20Reading/Distributed%20Gen%20Technologies%20Report.pdf
50. www.netl.doe.gov/publications/proceedings/01/carbon_seq/7c2.pdf
51. www.nrel.gov/docs/fy01osti/30554.pdf
52. www.eia.doe.gov/oiaf/forecasting.html
53. www.eia.doe.gov/cneaf/electricity/epa/epata7.html
54. www.ecy.wa.gov/laws-rules/wac173407_218/Calculating%20cogeneration%20unit%20 emissions%20and%20compliance.pdf
55. www.bakerobrien.com/documents/PRISMDescription080320-A4.pdf
56. www.eia.doe.gov/oiaf/analysispaper/biodiesel/
57. www.bloomberg.com/markets/commodities/cfutures.html
58. www.eia.doe.gov/kids/energyfacts/sources/non-renewable/oil.html#Howused
59. www.repartners.org/tools/pdf/Biodiesel.pdf
60. attra.ncat.org/attra-pub/switchgrass.html
61. www.eia.doe.gov/cneaf/coal/quarterly/co2_article/co2.html
62. tonto.eia.doe.gov/dnav/ng/ng_cons_sum_a_EPG0_VC0_mmcf_a.htm
63. www.ecy.wa.gov/laws-rules/wac173407_218/Calculating%20cogeneration%20unit%20emissions%20and%20compliance.pdf
64. www.grda.com/Electric/generation.html
65. *IPCC special report on Carbon Dioxide Capture and Storage*. Prepared by working group III of the Intergovernmental Panel on Climate Change. Metz, B., O.Davidson, H. C. de Coninck, M. Loos, and L.A. Meyer (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp
66. www.coal.org/roadmap/index.asp